SUCCESSFUL G1 CRUSHED STONE BASECOURSE CONSTRUCTION

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ABSTRACT

G1 Crushed Stone for base course is not the same thing as crusher-run and it is not only a matter of density. It was developed during the late 1950's from single stage crusher-run material that complies with Fuller curve particle grading and very strict material and construction specifications. Closure on this development and its capabilities was achieved during the South African Heavy Vehicle Simulator (HVS) test program during the 1980's, resulting in the conclusive proof that a properly constructed G1 Crushed Stone layer can be used for pavements with a bearing capacity up to 50 million standard axles (MISA) repetitions. This discussion sketches this development but concerns itself mainly with the slush-compaction construction process of a G1 layer and those aspects which directly monitor its success.

1. INTRODUCTION

G1 Crushed Stone for base course is not the same thing as crusher-run, and it is not just a matter of density that makes the difference.

G1 Crushed Stone was developed from single stage crusher-run material when during the late 1950's some observant Engineers noticed that this material would sometimes, after a sudden downpour and towards the end of its compaction cycle, exhibit the tendency to expel some of its fines (minus 0.075mm material), resulting in the aggregate "locking up" into a hitherto unknown tightly knit matrix, instead of becoming unstable as do other gravels under similar circumstances. This phenomenon was investigated and the results and conclusions applied to various experimental test sections until it could be controllably replicated. Refer to Figures 1 and 2 for schematic illustrations of the evolution of G1 and the impact this has had on the road infrastructure industry (Jooste and Sampson, 2005)

Closure on this development and its capabilities was achieved during the South African Heavy Vehicle Simulator (HVS) test program during the 1980's by using in-service G1 base course roads. The conclusion was that a properly done Crushed Stone layer could be used for pavements with a bearing capacity of up to 50 million standard axles (MISA) repetitions. It is exceptionally water resistant and the only unbound road building material found to increase in bearing capacity ("make muscle") to accommodate any increase in loading up to the point of rupture of the aggregate itself, without noticeable traffic moulding. However, this comes at a premium – it has to be produced and constructed to very tight specifications.

Note that, while there are a number of aspects important to successful G1 Crushed Stone application, such as pavement composition, construction, maintenance and rehabilitation, this discussion will concern itself mainly with the construction process of a G1 layer and those aspects which directly monitor its success.

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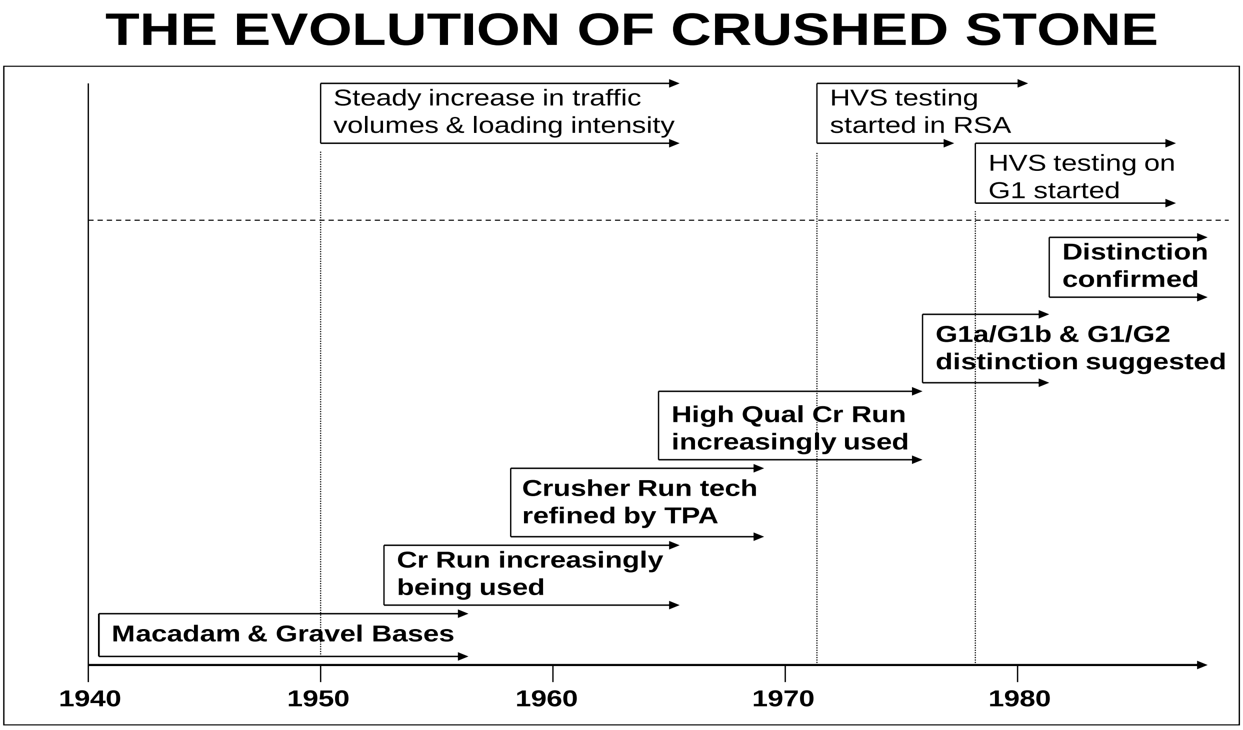

Figure 1: Schematic illustration of the evolution of G1 Crushed Stone from crusher-run (Jooste and Sampson, 2005).

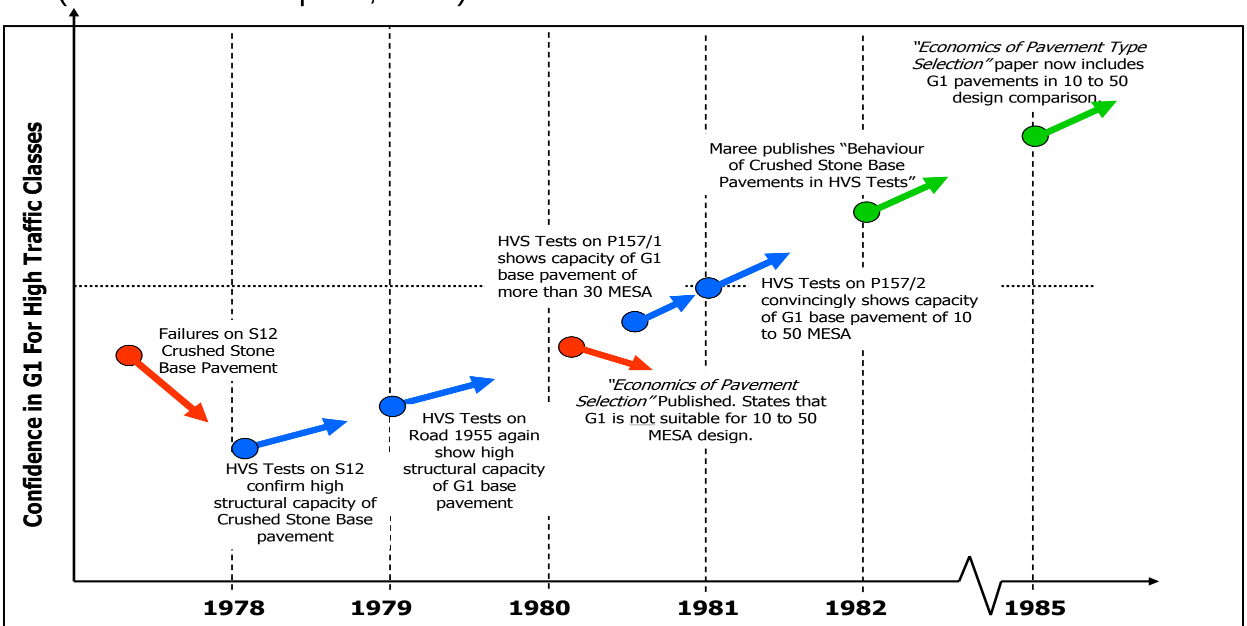

Figure 2: Summary of impacts on the use of G1 bases for high traffic loading designs (Jooste and Sampson, 2005)**.**

2. DEVELOPMENT AND SPECIFICATION

Some reverse engineering analysis was applied to this phenomenon and it was concluded that if conditions were just right, the crushed particle fractions could be packed together so tightly as to approach the state of pre-fracture. At first this concept seemed rather preposterous and like a pretty tall order to even consider simulating under normal road building conditions. Basically it meant that a jig-saw puzzle had to be reconstituted with random pieces into the original image.

Applying basic soil mechanics, it is known that the densest packing of particles is achieved when the grading of the material conforms to a Fuller curve grading (Fuller et al, 1907). Hence, various Fuller curve grading compositions were reconstituted from separated-out crusher-run aggregate and compacted in laboratory as well as field experimental sections. The following were observed:

- The aggregate fractions must virtually be "packaged" to interlock such as to form an aggregate matrix that approaches the condition of the intact parent rock – so called a "solid density". This state of interlock is manifested visually on the surface of the layer by a well knitted aggregate mosaic with only the slimmest line of inter-aggregate fines. Also, tapping the layer with a geological pick or other similar object, results in a "ringing" sound quite distinct from the sound made by normally compacted aggregate or gravel.
- The required final state of particle interlock results in a density much higher than hitherto used in road building, and cannot be expressed meaningfully in terms of Mod AASHTO (inter alia because determining an impact derived maximum density on a totally non-cohesive aggregate matrix delivers a very unreliable result). A more consistent result is obtained when the density is expressed in terms of the Specific Gravity or "solid density" of the aggregate - Solid Relative Density (SRD).
- Allowance can be made for enclosed voids within the aggregate (Apparent Relative Density or ARD) as well as cracks and fissures on the surface of the aggregate (Bulk Relative Density or BRD). Of the three methods SRD results in the higher target density, followed by ARD and BRD, which has a noticeable effect on the final interlock. Development of G1 was based on SRD and later also ARD. The difference between these two targets is dependent on the rock type and quality and is in some instances negligible for practical purposes. Indications are that 88% of SRD is actually the minimum required for the performance expected from such a layer - equivalent to about 106% Mod AASHTO density, according to parallel tests.
- The particle grading of the aggregate matrix is of utmost importance in this process. The conclusion reached was that "there must be just enough of each particle size to fill (all) the inter-particle voids", in other words, it must conform to a Fuller curve grading. Mindful of the fact that in terms of shear strength "size matters" and also impacts on constructability, a compromise had to be reached and it came down to a 37,5mm maximum size aggregate matrix (some road authorities prefer a maximum size aggregate of 26,5mm for certain applications), continuously graded to comply with a grading envelope defined by two Fuller curves, one to the power of 0.3 (fine boundary) and the other to the power of 0.5 (coarse boundary).
- The aggregate had to be very resistant to general construction impacts and high energy compaction forces that had to be applied to achieve the final state of interlock required. No structurally inferior or contaminated material could be tolerated. This also holds true for the possibility of chemically degrading and/or resurgence of plasticity, such as found with basic crystalline rock, and chemo-mechanical interlock disruption as found under excessive soluble salt content conditions. Only fresh un-weathered and sound rock should be used for G1.
- The plasticity of the G1 aggregate matrix must be as close as possible to zero – the argument being that the matrix must contain as little as possible material that may affect the particle interlock negatively and thus the shear strength of the compacted material – the layer must be as moisture insensitive as possible. Hence, also the avoidance of basic crystalline rock, especially when containing clay forming smectite to any degree, without pre-treatment with lime.

- In order to achieve the above requirements the material for G1 has to be crushed from "fresh" un-weathered rock. No material other than from the parent rock may be used or added to correct the grading. Hence, smooth un-crushed river gravel is not recommended, even if it has the proper grading, because the matrix will lack effective interlock and hence resistance to traffic moulding.
- In order to provide a firm support ("anvil") upon which to compact the G1 aggregate matrix and also withstand the copious amounts of water associated with the slush-compaction process, the subbase must be well cemented to at least C4 standard (750-1500 kPa UCS).
- The other cautions regarding the soundness of material, such as hardness, flakiness, soluble salt content, etc., used for road building are just as important, if not more so, because of the high levels of energy and moisture applied during construction as well as during the service life of the material. This resulted in the specifications given in COLTO (1998) and TRH 14 (1985) and the now well-known final grading envelope shown in Figure 3.

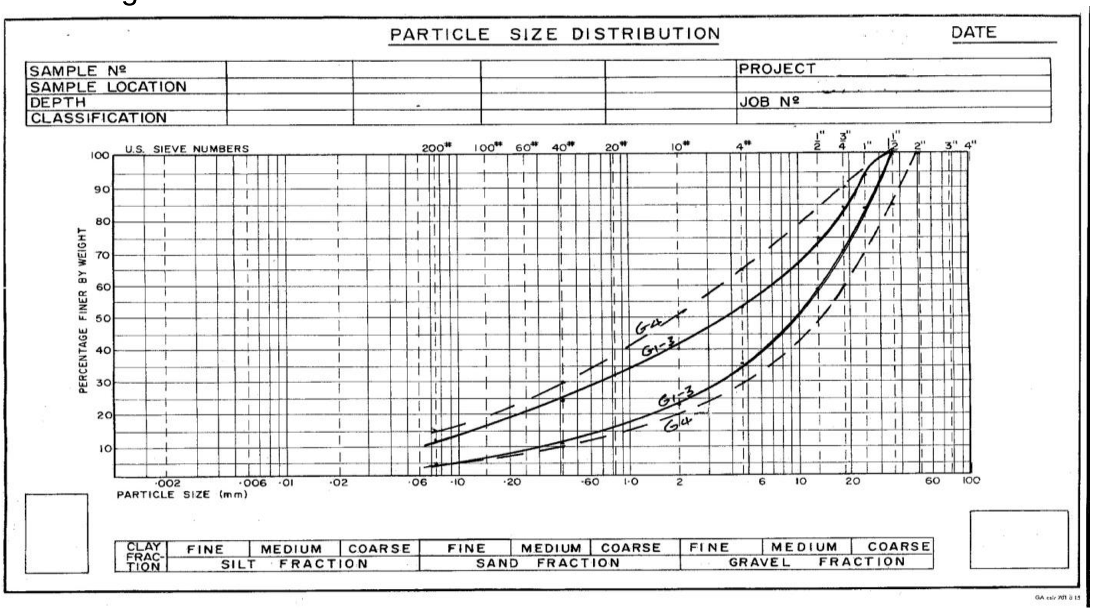

Figure 3: COLTO G1 to G4 grading specifications illustrated.

On occasion it has been noticed that it is possible to achieve the specified density before applying the final slush-compaction process. Fortunately it is relatively easy, in such cases, to see that the expected surface mosaic (interlock) has not been achieved (refer to Step 12 below). This can happen when one or more of the following conditions occur:

- An aggregate matrix with a slight excess of fines or on the fine side of the specification envelope can deliver the "correct" density without slush-compaction but will not deliver the typical G1 shear strength and traffic moulding resistance.
- The surface texture of the aggregate is relatively smooth so that it takes very little effort to achieve aggregate lock-up. Conversely, the matrix can also then be de-interlocked easily and lose the interlock associated high shear strength.
- The target density has been miss-calculated, especially when related to Mod AASHTO, and considering the difference between SRD, ARD and BRD discussed above, resulting in a relatively low target density attainable without proper interlock.
- Some slush-compaction or water-roll actually took place under the normal compaction process, without being noticed. Under this condition the expelled fines on the surface of the layer might not have been broomed off completely, resulting in a thin layer of fines which will cause poor adhesion and stress transfer between the base and the surfacing.

3. CONSTRUCTION PROCESS

Constructing a G1 Crushed Stone base layer is a very exacting process and the specifications must be stringently applied if it is to perform as expected and be a cost-effective option. However, from experience it requires little extra effort above that required for normal gravel compaction, when executed correctly. The following has to be done sequentially:

Step 1: The importance of accepting only in-specification G1 material on site cannot be over-stressed – it can mean the difference between getting the job done cost-effectively and going bankrupt. Inspect the target grading from the crusher for compliance with the specification for the project (or COLTO) before ordering. Suggest and negotiate corrections to the crushing plant manager timely before ordering. Inspect each batch of crushed material delivered for compliance with the target grading and other specifications agreed upon, before acceptance. Stockpile the material from the crusher onto a prepared site from which it can be reloaded without the danger of being contaminated/degraded, or stockpile it directly onto the road. Refer to Photos 1 and 2.

Photo 1: Loose G1 material.

Photo 2: G1 material stockpiled on road.

Step 2: Provide a clean, dampened and well stabilized and leveled subbase as anvil upon which to construct the G1 basecourse – keeping in mind that a G1 layer requires copious amounts of water and high compaction energy to compact and interlock. A poorly leveled and rough subbase surface will encourage segregation of the aggregate during placing of the material and affect the slush-interlocking process adversely, even to the point of impossibility.

Note: It is strongly recommended that a G1 test section, prepared similarly to the pavement under construction, be laid to familiarize one with the material from and the most suitable compaction process for, the particular crusher/rock source and ultimately to demonstrate competence.

Step 3: Calculate the spacing of the truck loads to be stockpiled in the middle of the road on the subbase according to the truck load volume to achieve the compacted layer thickness. Avoid using varying truck sizes, which will cause varying dump spacing and material movement which may cause aggregate segregation and layer thickness variation. If possible have the aggregate being transported damp to inhibit segregation during loading, transportation and dumping. Do not hose it down with a stream of water, either in the main stockpile or on the truck, since this will certainly cause segregation of the fines and lengthen the on-site mixing process and/or complicate the final slush-compaction process. Just dampen the material enough to cause the fines to adhere to the larger aggregate. Visually inspect the material for obvious grading non-conformity and deleterious content.

Step 4: Moisten the stockpiled aggregate again one day prior (at least 12 hours) to constructing the layer, if it has dried out in the mean time, once more taking care not to induce segregation of the fines. This is done by only slightly flattening the aggregate dumps with a motor grader such that a watering truck can just drive over the dumps at crawling speed to moisten the material to below, but as close as possible to, optimum moisture content (OMC). Check visually that the fines are not washed off from the larger aggregate.

Step 5: Spreading of the damp material on the day of construction is done with a motor grader by gently taking successive fully laden blade-sized loads off the stockpiles on the subbase across the full width of the available subbase. The material must not be disturbed unnecessarily – rather place it in close proximity to the stockpile from which it was cut. Do not storm into the dump and try to flatten it in one fell swoop. This will only succeed in segregating the material. If the spread material appears to be too dry it may be moistened and mixed-in to the full depth of the layer and with the grader blade sweeping the surface of the subbase. (Do not use a disc harrow for this purpose since it will tend to segregate the material as well as damage the subbase.) If the material starts deforming under compaction, it usually is too wet. Let it dry out sufficiently before continuing. If the moisture content is just right, the material may be placed as soon as possible. This is done at an even pace (≈ 8km/hr) to the correct thickness, allowing for a bulking factor of 1,4 to 1,5, as well as a small windrow of material on one side of the road for unforeseen layer thickness correction purposes.

Note: The OMC of G1 material usually lies between 4% and 6%. A very low OMC indicates a lack of fines in the mix, which means that the final slush-compaction process will be difficult to accomplish, whereas a very high OMC indicates excessive fines, which will lengthen the slush-compaction process because of the additional fines that will have to be extracted to achieve proper interlock. (Keep in mind that the OMC of a material is roller/compaction equipment sensitive.)

Step 6: The layer can now be shaped according to the specification by motor grader. Depressions may be corrected by mixing in additional material. If the shortage of material occurs over a short distance (< 15m), Crushed Stone material may be spread on the area with the ripper teeth of a motor grader and mixed in thoroughly. If the depression is longer than about 15m it is advisable to remix all the material over a distance of at least 100m after the additional material has been added. Excess material may be removed similarly. Be careful not to contaminate the G1 material with the shoulder material where it consists of normal gravel. All layer thickness corrections must be done in this phase, before any compaction is done.

Step 7: The compaction process must start as soon as the layer thickness and shape is to specification. To avoid rolling the layer out of shape, always initiate the process with the first pass on the outer edge of the layer and move successively with each pass towards the centre line or highest point of the cross section. When initiating the compaction process with a vibratory roller, do the first pass in "static" mode. This can be followed by two passes with the vibration at relatively low frequency and high amplitude at a speed of 3 to 4 km/hour.

Step 8: Do any layer/shape corrections at this point before it is too firmly compacted. Initiate the first cut at the windrow on the side of the road and always with the grader blade fully laden with the graded material. The layer must be shaped again to specification. Apply the vibratory roller again for two passes at a speed of 4 to 6 km/hour, but this time at a relatively high frequency and low amplitude. Hereafter, the layer should have the correct elevation/thickness and shape and be stable enough to receive its final "windrow fines distribution cut", if necessary. A visually even, well-graded, appearance will enhance the slush-compaction (slushing) process.

Step 9: The layer should now be rolled with a heavy pneumatic-tyred roller (upwards of 17 m ton) in combination with heavy static steel-tyred rollers. Ensure that the moisture content is correct for the equipment used. It is important to lead with the driven wheel/s of the roller, especially initially, to avoid the formation of a compaction negating “bow wave” of material in front of the roller-drum.

Step 10: Rolling must continue until the layer exhibits no (or very little) movement under the wheels of a heavy roller, before the slushing process may begin. At this stage the density of the G1 material should be in the order of 85% of SRD/ARD. If the slushing process is started too early the layer will become unstable and even expel the larger (sandy) fines, which will further complicate and delay the slushing process.

Step 11: The slushing process (slushing) can commence immediately when the layer is stable enough, or delayed for a day or two to dry out and regain stability. However, do not let the layer dry out unnecessarily before starting with the slushing since this might delay the onset of the actual slushing action itself. Basically the slushing process is initiated by thoroughly wetting and rolling 40 to 60m sections of the layer at a time (depending on the number of rollers available) with heavy static rollers. The water must be applied at the highest points of the cross section or gradient and utilized as it runs down to the lower points. Keep in mind that using relatively light rollers can result in only the upper part of the layer being properly slushed. The fines (< 0.075 mm!) expelled must be broomed to areas deficient in fines, and eventually off the road. Finally all slush-fines must be removed from the road with heavy duty hand brooms or light mechanical brooms before it dries out and hardens to a crust. Take care not to overdo the brooming and so loosen/destroy the aggregate mosaic.

Note: The minus 0,075mm fraction is utilized as a “lubricant” to ease the relative movement between the larger particles towards achieving intimate stone upon stone packing, squeezing (slushing) the excess fines out of the matrix in the process. It was found advantageous to have the percentage minus 0.075mm fraction slightly higher (2% - 3%) than required to satisfy the Fuller curve grading, especially when working with material which is on the coarser side of the specification envelope. This slight excess of fines must eventually, of course, be slushed out completely to end up with the required Fuller curve grading and interlock after slushing – so this point must not be over-done. The slushing process normally only increases the overall ARD by 2% - 4%, however, the shear strength and performance of the material increases dramatically in so doing.

Step 12: If one keeps in mind what the slushing action is supposed to accomplish it will not be difficult to monitor the process and observe when the goal has been achieved. Hence, look out for the following indicators:

- Slight movement of the layer under the rollers might be observed at the onset but should decrease and stop as soon as the air bubbles and fines start being expelled.
- Observe that air bubbles will appear on the surface as soon as the slushing process takes hold – indicating that the aggregate is being moved closer together, expelling the air from the voids in the matrix. This phenomenon will cease during the final stages of the slushing process.
- Similarly, observe that fines (creamy in nature) will start appearing on the surface and should be broomed to the side of the road or to coarser areas. Keep just enough slush on the road to assist with the slushing process. A sign that the slushing process has been completed and should be stopped is when the slush being expelled clears up until it is mainly water. If this indicator is ignored, sandy textured fines (the fraction above the minus 0.075mm) usually starts being expelled.

As the aggregate becomes more interlocked the surface will increasingly exhibit a densely knitted aggregate mosaic with a minimum of fines being visible in between particles. Refer to Photos 3 to 5 for a comparative view of the surface of Crushed Stone material variously compacted. Some road authorities do not apply the slushing process fully but only a mild form of it termed “water-roll”, more as a surface finishing process (Photo 4), which results in an improved surface texture compared to normal gravel compaction (Photo 3) but not the interlock and traffic moulding resistance. The final mosaic surface should at least look something like that shown in Photo 5. Photo 6 shows a slush-compacted G1 layer on a Heavy Vehicle Simulator test site from which a piece was cut by diamond studded saw blade. The exposed G1 face had the appearance of high stone content concrete – a sight that beguiled many a test site visitor.

At this point the aggregate is interlocked so intimately that applying more energy will usually only succeed in fracturing the aggregate itself, creating more fines and hence degrading the interlock and shear strength of the G1 matrix.

Note: If, at any time during the rolling process, the layer should become unstable due to excess moisture, rolling should be ceased and the layer allowed to dry out sufficiently before continuing with the rolling process. However, if the layer does not regain its stability, the whole process, starting with Step 1, should be redone by plowing the layer up and remixing the aggregate matrix, placing and rolling it, as described above. This is not a sure fire process since the grading of the material may now have changed significantly, have been contaminated with foreign material and/or the subbase may have been damaged, etc., so as to make it impossible to get the desired end result - necessitating discarding the material and bringing in fresh G1 material.

Photo 3: “Gravel-compacted” G1 material.

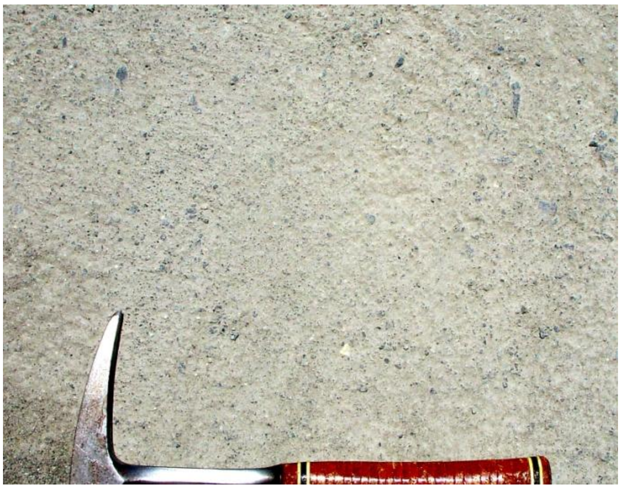

Photo 4: “Water-roll compacted” G1 material.

Photo 5: “Slush-compacted” G1 material.

Photo 6: G1 layer cut like concrete.

Step 13: After the above has been done the layer should be allowed to dry out somewhat for about 12 hours and no traffic should be allowed on it. The layer can then receive its final “dry roll” to bed the surface aggregate even better since, although not visible, the aggregate particles will be slightly raised because of the excess water around and under the aggregate which should now have evaporated.

Step 14: Density/quality control should be done within 24 hours when the material is still damp (moisture content of about 50% OMC in the upper portion of the layer) and the possibility of disturbance minimized. COLTO adopted density control by nuclear apparatus, mainly because the possibility of disturbing the compacted aggregate matrix is less than when excavating a sand replacement hole. This is a moot point since both have their pros and cons. (It delivers an "indicator" with which to "engineer", pretty much the same as any other material specification and quality control measure.)

4. CONCLUSIONS

The following conclusions may be drawn from the above discussion:

- Crushed Stone material for G1 basecourse construction is a highbred development from crusher-run material, applicable to superior road basecourse construction.
- In order to achieve the high degree of particle interlock, the material for G1 basecourse must comply with a very specific Fuller curve particle distribution as well as very strict material quality control specifications.
- Successful conclusion of the construction process of a G1 layer requires a very precise set of actions which have to be executed sequentially and correctly.
- Understanding the aim and processes, makes for light work and effective corrective measures when necessary.

5. RECOMMENDATIONS

The following recommendations are made towards ensuring successful G1 Crushed Stone base course construction:

- Have the correct specifications and technology about G1 basecourses.
- Know the specifications and technology of G1 basecourses.
- Know that the specifications and technology is correct.
- Teach this technology correctly.
- Apply this technology to G1 basecourse construction.
- Deliver a G1 basecourse if so specified and agreed to.

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