EROSION OF COMPACTED WEARING COURSE GRAVELS RELATING MATERIAL GRADING, PLASTICITY AND COMPACTION TO EROSION POTENTIAL

H RANGE and E HORAK*

Masters student at the University of Pretoria,
currently Ndodana Consulting Engineers (Pty) Ltd, PO Box 8623 Centurion 0046.
*HOD Civil and Biosystems Engineering, University of Pretoria.

ABSTRACT

Every year, more than 150 million tons of gravel is stripped from our roads and 4 million tons of dust that binds the gravel blows away in the wind. This gravel needs to be replaced, but at current replacement intervals appropriate sources will eventually run out (DOT, 2004a). Gravel loss is caused by a combination of natural weathering and motorised traffic factors. Mechanisms of friction and whip-off are associated with motor vehicles, and rain, stormwater; wind etc. are natural occurring phenomenon (Paige-Green, 1989b). Erosion is one such mechanism causing the loss of gravel wearing courses. Erosion is due to a combination of steep grades, rainfall, environment, material characteristics and the water shedding capacity of the road profile.

This paper reports an exploratory laboratory study on the material characteristics of compacted wearing coarse gravels as they relate to erosion potential. The significance of particle size distribution and shape, compaction and plasticity (PI) were quantified. The CSIR Erosion Resistance Testing Device, that simulates erosion conditions in the field, was used for determining erosion potential. Three types of weathered granite wearing coarse material, with a spread in Plasticity Index were used to create a plasticity envelope in which the effect of increased compactive effort were investigated. Findings from a literature review and the experimental program results were utilised to formulate an interim erosion–material characteristics guideline. Even as an interim guideline it can provide helpful information as an aid for design situations and engineering decisions concerning gravel roads.

1. INTRODUCTION

The transport infrastructure of a country constitutes probably the most important factor influencing economic sustainability. This is very evident in developing countries depending heavily on their road network for logistical and economic activity. Approximately seventy nine per cent of South Africa's road network consists of unpaved roads. This is overwhelmingly more than the length of surfaced road. The sum of the surfaced roads of the 9 provinces is 63 153km, while gravel roads constitute 300 978km of the total 364 131km of road length. Every year, more than 150 million tons of gravel is stripped from our roads and 4 million tons of dust, that binds the coarser gravel together, blows away in the wind. This gravel needs to be replaced, but at current replacement intervals appropriate sources will eventually run out (DOT, 2004b).

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It is clear that the Department of Transport (DOT) realises the situation and the importance of the unsurfaced road network: “Because of its extensive length and susceptibility to erosion, both by traffic and weather, the maintenance costs are disproportionately high when measured against vehicle kilometres of travel. Gravel roads carry only five per cent of the total daily traffic and the provinces currently spend about R10 000 per km per year on maintenance. Extending this to the network as a whole would imply a need of R6 billion annually” (DOT, 2004a). This is a very high cost, especially when new road infrastructure also needs to be budgeted for.

There is a significant economic and environmental incentive to minimise erosion on unsurfaced areas, and to combat the considerable impact it has on riding quality, safety, travel costs, maintenance, etc. An insight into the role of material/road characteristics and compaction could be the key to erosion prediction of compacted unsurfaced roads. The use of conventional and unconventional chemical gravel stabilisers preventing erosion due to water action also need to be understood. This research project was aimed at contributing scientific findings and discussions on more effective material use, and to promote better engineering decision making, more cost effective road design and construction knowledge to the road building community.

The primary objective of this study was to investigate the material characteristics of compacted wearing coarse gravels that relate to their erosion potential. The significance of particle size distribution and shape, compaction and Plasticity Index (PI) were quantified. Secondary objectives were: to formulate an interim erosion–material characteristics guide in an attempt to define and describe erosion potential in terms of storm water flow characteristics, and quantify material preservation potential in terms of particle size distribution, compaction effort and Plasticity Index (PI); provide more insight into the role of material characteristics in explaining erosion potential. In the process, it also served to evaluate the CSIR Erosion Resistance Testing Device and test method as a standard laboratory test.

2. EXISTING EROSION TESTS

Various methods have been used to measure erosion on different elements of surfaced, unsurfaced and concrete pavements. Most agencies have developed and modified tests to suit their particular needs (Jones & Ventura, 2002). It is clear that findings on material characteristics in terms of durability, abrasion and weathering could be functional in relating material characteristics to erosion resistance. The following devices and methods were identified as being appropriate in erosion investigation: The rotational shear device, jetting, and brush tests where found to be the fundamental tests. Only limited information was found on tests that could simulate wind shear to investigate wind erosion, and more focus was therefore given to water induced erosion tests. Other tests evaluated in the literature study included the Slake-durability Index test (Franklin & Chandra, referred to by Bell, 1987) and the Erosion Test for Soil Cement (Oswell & Joshi, 1986).

The detailed literature study revealed that no suitable erosion test could be found in the literature, except the test that was developed by the CSIR to suit the requirements of fit-for-purpose certification (Jones & Ventura, 2002) of road additives. This test was found to be the closest in simulating erosion loss due to the sheet flow of stormwater over a compacted road surface, which satisfied the requirements of this experimental program.

3. CSIR EROSION RESISTANCE TESTING APPARATUS

In the development of the erosion test, the CSIR identified that an apparatus, which allowed water to flow over a prepared specimen at a constant rate (Figure 1), was required to simulate water flow over a compacted road. The apparatus was designed to accommodate specimens (in terms of size, compaction and materials) used in the abrasion resistance test in such a way that they could be easily placed and secured without damage (Figure 2 show 1-water inlet, 2-water jets, 3-specimen). A series of prototypes were used to establish an appropriate configuration of water jet, specimen location, flow angle and flow intensity. The apparatus was designed to fit into a typical laboratory sink, and can be set up quickly and easily (Jones & Ventura, 2003).

Since the water pressures used would be relatively low (the apparatus had to simulate water flowing over the road, not water impact), the distance between the water and the specimen needed to be optimised to minimise decrease in velocity of the water contacting the specimen. After some experimentation, the distance was established to be most suitable between 90 and 115mm, and a distance of 100mm was chosen. An angle of 35º proved to be appropriate to allow for the runoff of water and soil (Jones & Ventura, 2003).

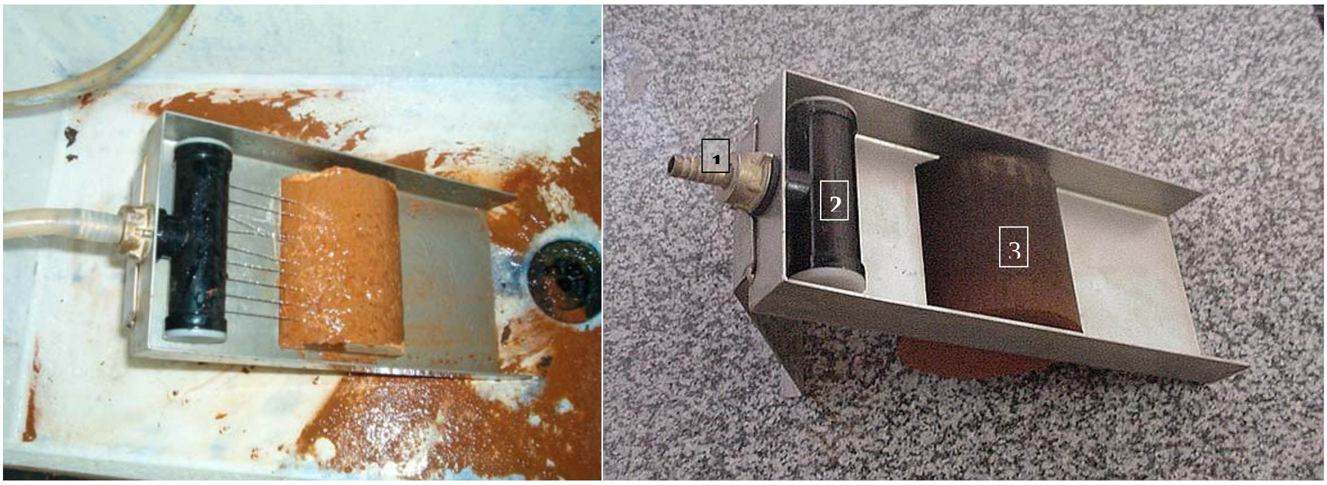

Figure 1: Water simulation

Figure 2: CSIR apparatus (Jones & Ventura, 2003)

Specimens are prepared by calculating and weighing out the correct quantities of material and water. The material and water are thoroughly mixed and preserved in a plastic bag before compaction is done. A steel mould having an inside diameter of 100 mm and 175 mm in length, together with two end caps (30 mm thick and diameter that will fit snugly into the mould) are used to compact a specimen. A hydraulic press is used to press into the mould to form a specimen 100 mm in diameter and 115 mm in height. An extruder is used to extract the specimen from the mould, which fits into the base of the endcap (which is used as a base plate) (Jones & Ventura, 2003).

The full length of the specimen needed to be subjected to water flow, which required nine jets spaced at 1.0 mm intervals. This eliminated the testing of only one area that may not be representative of the whole specimen, and takes the variability of soils into account. Different sizes of jets where experimented with to obtain a suitable water force that could initiate erosion. A jet size of 1.0 mm proved to be suitable in terms of water jet pressure, and precision drilled to maintain the correct spray angle (Jones & Ventura, 2003).

A constant-head delivery system is attached to the apparatus to ensure consistency in testing. Various water heights were investigated. The water pressure produced from a height of 0.5 m did not adequately erode the specimens, with untreated sand specimens losing between 2.0 and 3.5 per cent of their original mass. At 1.0 m the loss was between 16 and 20 per cent, while treated specimens lost significantly less. A height of 1.0 m was therefore selected to ensure that erodible, non-erodible, treated and untreated materials could be clearly distinguished (Jones & Ventura, 2003).

The optimum duration of the water flow was then assessed to finalise the test method development. After a series of experiments using different test times and water flows, a period of five minutes was selected. Five minutes provided sufficient time to distinguish between the erodibility of different soils and the effectiveness of treatments (Jones & Ventura, 2003).

4. EXPERIMENTAL PROGRAM

This research was predominantly an exploratory laboratory study that focused on the following material characterisation tests: Grading analysis, Atterberg limits, Maximum Dry Density (MDD), Optimum Moisture Content (OMC) and existing, as well as data from a new erosion test. The CSIR Erosion Resistance Testing Device, that simulates erosion conditions in the field, was used for determining erosion potential.

Investigations were done on a limited sample of common wearing coarse gravels used in the construction of gravel roads. This investigation was designed to supplement the broader based laboratory and field study done by Jones and Ventura (2003), which concentrated on the fit for purpose testing of chemical road stabilisers. Three types of weathered granite (Acid crystalline) wearing coarse material, a non-plastic type (PI=around 0), a medium-plastic (PI=around 8) and a highly plastic (PI>15) weathered granite were used to create a plasticity envelope in which the effect of increased compactive effort of 90%, 95% and 100% Mod AASHTO were investigated.

The results of the material characterisation tests are summarised in Table 1. Figure 3 provides a graphical representation of the particle size distribution of the three samples.

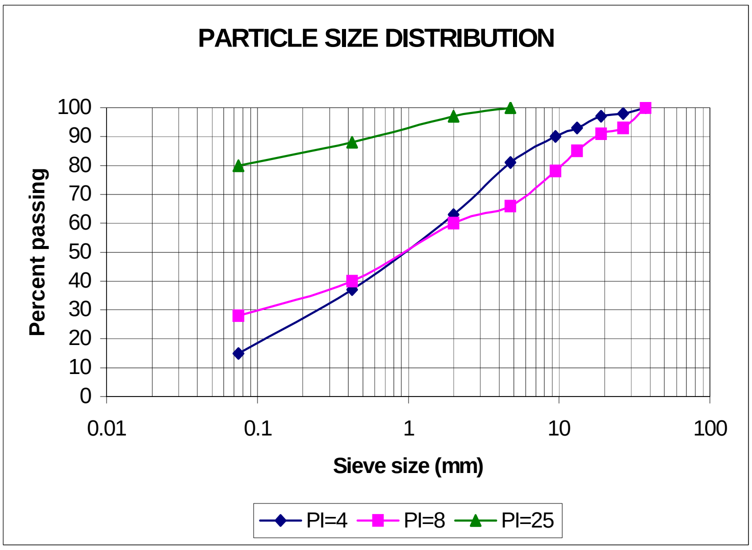

Figure 3: Particle size distribution

Table 1: Properties summary

PROPERTY	MATERIAL TYPE		
	Granite - HP	Granite - MP	Granite - NP
Liquid Limit (%)	53	26	18
Plastic Limit (%)	28	18	14
Plasticity Index (%)	25	8	4
Bar Linear shrinkage (%)	11.5	4.0	1.5
Percent Passing Sieve:			
37.5 mm		100	100
26.5 mm		93	98
19.0 mm		91	97
13.2 mm		85	93
9.5 mm		78	90
4.75 mm	100	66	81
2.0 mm	97	60	63
0.425 mm	88	40	37
0.075 mm	80	28	15
Maximum Dry Density (kg/m^3)	1606	2132	2084
Optimum Moisture Content (%)	23.6	7.2	7
Grading Modulus	0.35	1.72	1.85
Grading Coefficient	3	21.8	28.4
Shrinkage Product	1012	160	55.5
HP - Highly Plastic			
MP - Medium Plastic			
NP - Non-Plastic			

The relationship between shrinkage product, grading coefficient and performance of unpaved wearing course gravels was also evaluated (Figure 4) and the TRH 20 (1990) provided the following classification of the test materials:

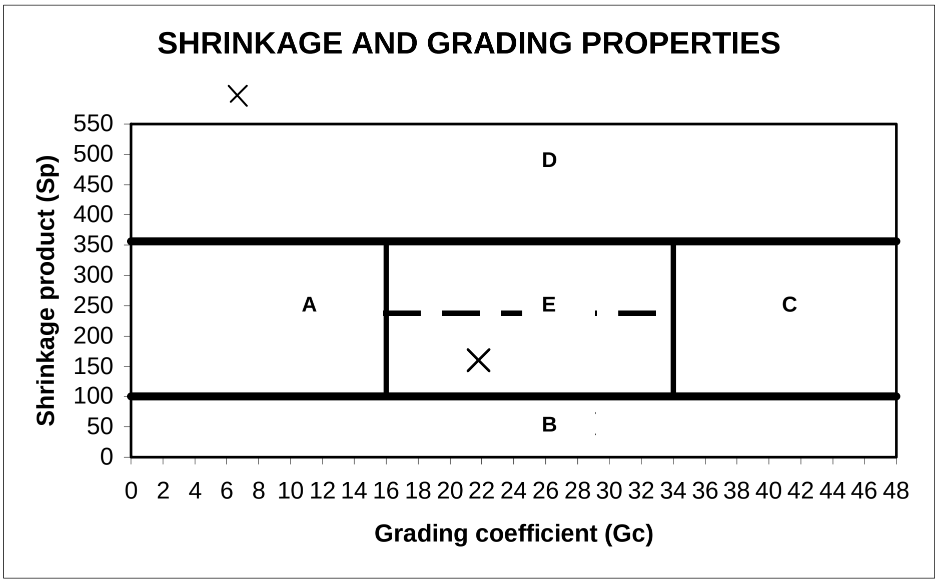

Figure 4: TRH 20 Classification

Non-Plastic Material (PI = 4)

This material fell in Zone B. These materials generally lack cohesion and are highly susceptible to the formation of loose material (ravelling) and corrugations. Regular maintenance is necessary if these materials are used and the roughness is to be restricted to reasonable levels (TRH 20, 1990). This material was sampled from an existing gravel road with excessive corrugations and loose material, which is also indicative of non-plastic characteristics.

Medium Plastic Material (PI = 8)
This material fell in the bottom half of Zone E shown in Figure 4. Materials in this zone perform well in general, provided the oversize material is restricted to the recommended limits (TRH 20, 1990). The bottom half of Zone E indicates that this is a good material, and that the material most likely wouldn't be dusty.

Highly Plastic Material (PI = 25)
This material plotted above Zone D shown in Figure 4. This material's shrinkage product is in excess of 550, and would tend to be exceptionally slippery when wet. The high Plasticity Index of 25 alone is already indicative of this possibility.

5. EROSION TEST RESULTS

A graphical summary of the erosion test results from the experimental program is contained in Figure 5. The erosion test results clearly show that increased density or increased compactive effort will drastically improve resistance to erosion irrespective of PI. Higher PI has an increased resistance effect on erosion resistance, but this is overshadowed by increase in compactive effort.

This has significant practical value as actual experiments with 98% Mod AASHTO density requirements on gravel roads in the Western Cape (Visser, 2005) has proven this aspect already.

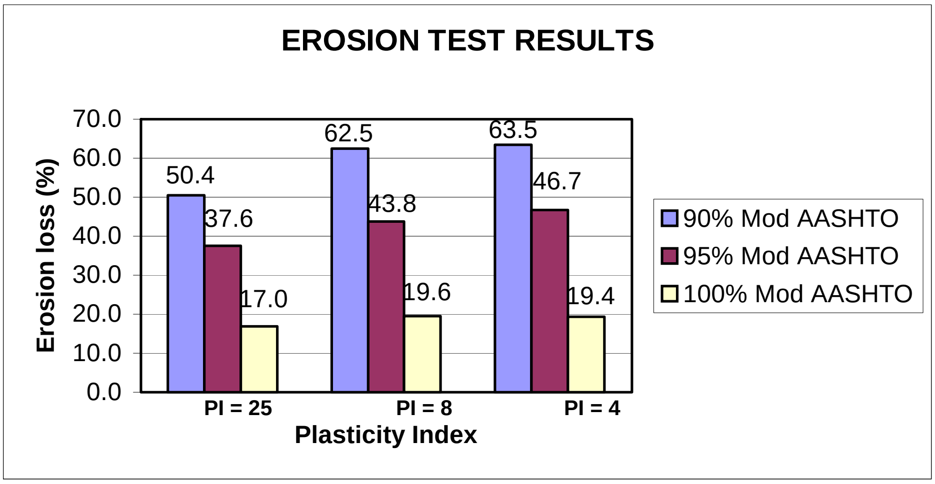

Figure 5: Graphical summary

6. GUIDE DEVELOPMENT

In the development of this guide it was attempted to define and describe erosion potential in terms of storm water flow characteristics, and quantify material preservation potential in terms of particle size distribution, compaction and Plasticity Index (PI) in terms of test done with the CSIR Erosion Resistance testing apparatus.

The relationships of erosion in terms of plasticity, compaction and maximum dry density were investigated and used to formulate an interim erosion-plasticity-compaction relationship identified in the experimental program and to relate it to material characteristics. Even though the sample size was limited it did give clear indications which can be improved on in future tests supplementing these explorative tests. The linear correlation of the erosion-plasticity-compaction relationship is supported by the plots for material PI = 4, PI = 8 and PI = 25 in Figure 6. All the materials indicated definite trends with very good correlations (R-squared values of 0.98 to 0.99).

These linear correlations were slightly modified and used to develop an interim guide as seen in Figure 7.

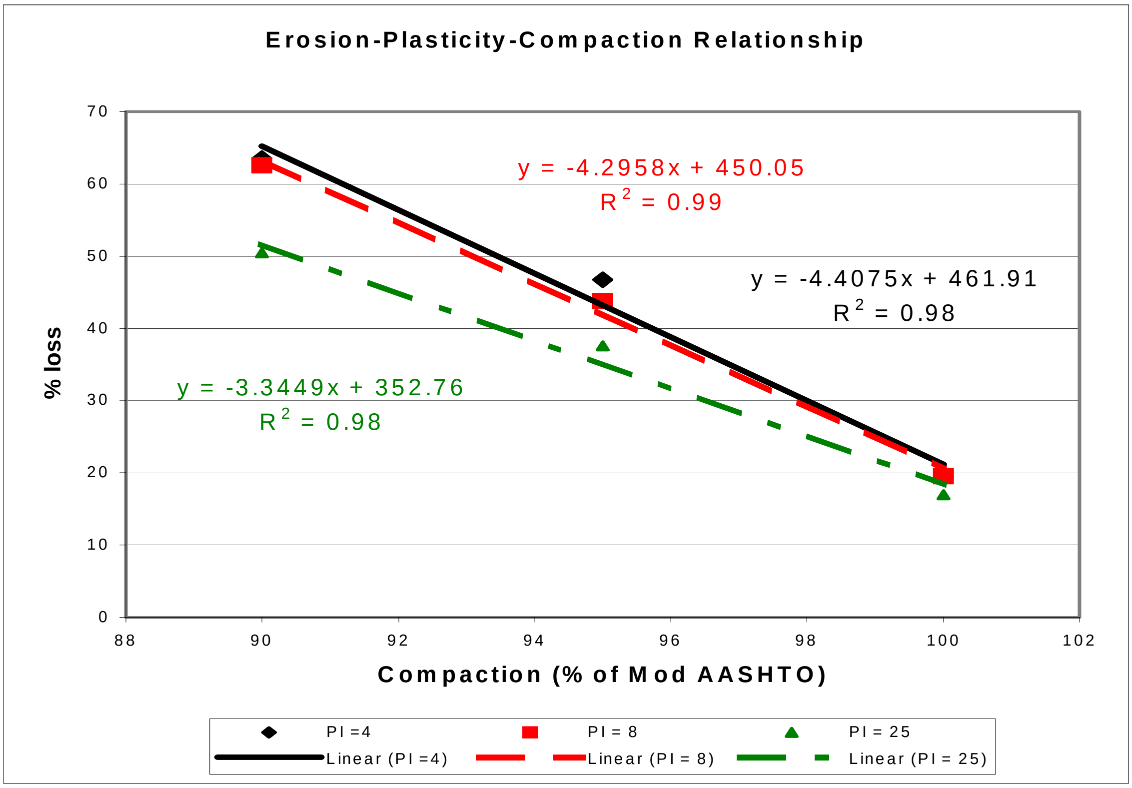

Figure 6: Erosion-Plasticity-Compaction Relationship

As indicated in Figure 7, a 30% loss is suggested as an interim limit. This tentative limit was developed by Jones and Ventura (2003) in their broader study on fit for purpose use of chemical stabilisers with gravel wearing courses. A material with a compactive effort of 95% Mod AASHTO will exceed the 30% interim limit on erosion (loss%) irrespective of it having a non-, medium- or high-plasticity. By increasing the compactive effort to 96.5% Mod AASHTO, the high-plasticity material (PI = 25) will meet the requirement, while a compactive effort of 98% Mod AASHTO will also meet the interim guide for medium and non-plastic materials.

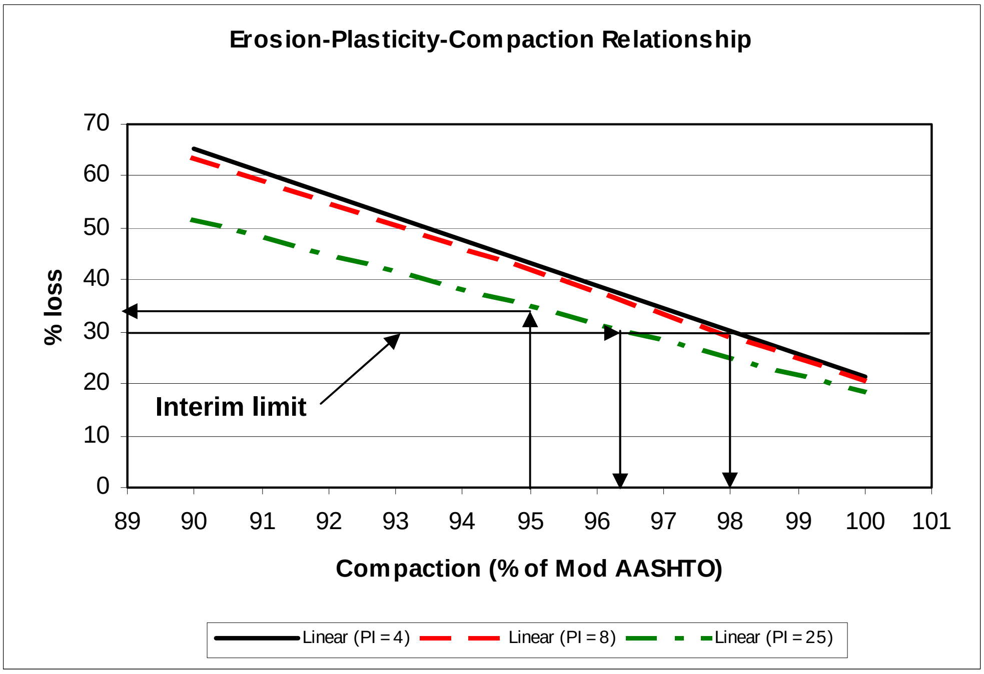

Figure 7: Erosion-Plasticity-Compaction Relationship Guide

The next question is normally which materials would benefit most from the use of chemical stabilisers to enhance erosion protection. Even though treatment with such conventional or unconventional soil/gravel stabilisers did not form part of this investigative limited experimental program, a further refinement of the information and criteria can be helpful in this regard. Results from numerous fit for purpose tests done by Jones and Ventura (2003) helped to establish erodibility zones.

The erodibility zones included in Figure 8 represent expected erosion levels as derived from visual observations of field performance and tests done with the CSIR Erosion Resistance testing device (Jones & Ventura, 2003 and Ventura, 2003). Figure 8 indicates the expected performance of the granite spectrum evaluated during the laboratory study. Four suggested zones can be identified:

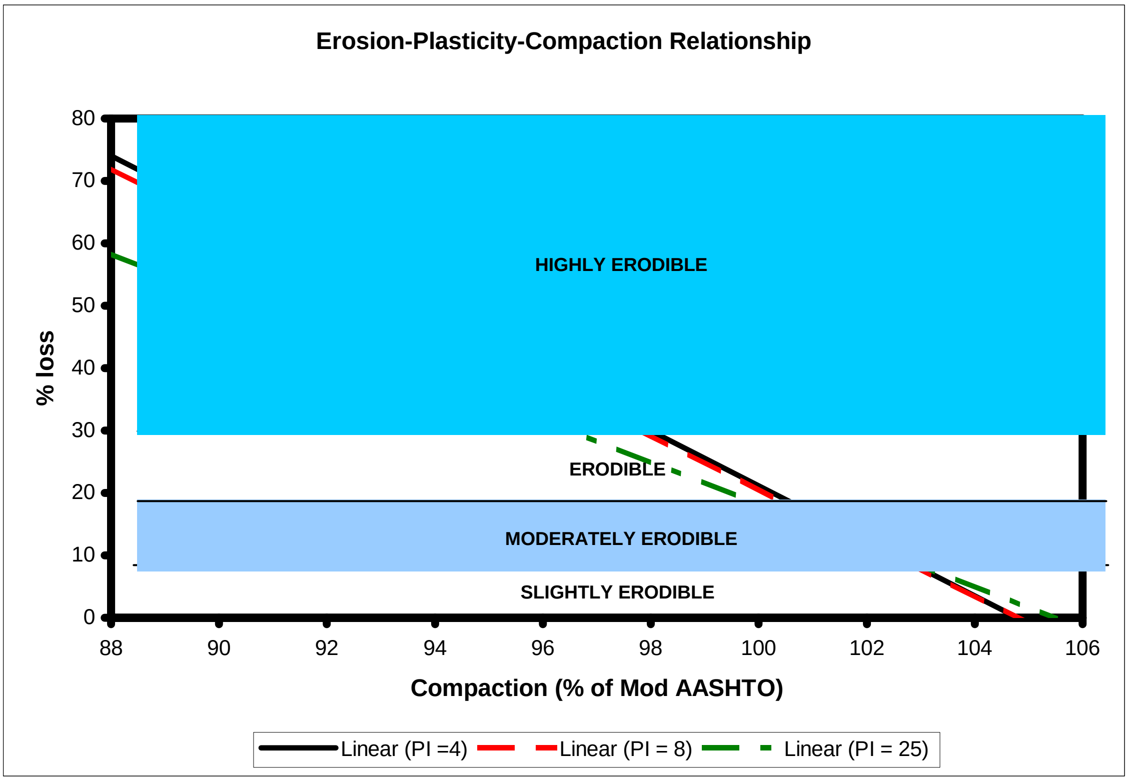

Figure 8: Modified Erosion-Plasticity-Compaction Relationship Guide

HIGHLY ERODIBLE – A material with a ≥ 30 % material loss is seen as a material with very high erosion potential, and is thus very erodible. Such materials would have to be chemically or mechanically modified to acceptable levels of material loss for use in the road structure or otherwise discarded as wearing course gravels. As indicated before, an increase in compactive effort can easily improve the erosion resistance to erodible.

ERODIBLE – A material that has a material loss of between 18 and 30 % has high erosion potential and would also need to be chemically or mechanically modified to acceptable levels. A position closer to the slightly erodible area would noticeably indicate a better performance. An increase in compactive effort can improve the erosion resistance significantly towards moderately erodible.

MODERATELY ERODIBLE – A material that has a material loss of between 8 and 18% material loss has moderate erosion potential. Chemical or mechanical modifying methods are only a consideration for these materials, but an increase in compactive effort can improve the erosion resistance significantly towards the slightly erodible area.

SLIGHTLY ERODIBLE – Material loss of 0 to 8% is seen as an acceptable loss for the use of materials in wearing course gravels. Materials in this area have a slight potential to erode, but would not have an erosion problem when used. An increase in density will obviously improve the resistance to erosion loss, but density levels may tend to become impractically high.

7. CONCLUSIONS

7.1 Erosion due to waterflow over gravel wearing courses has been identified as a major cause of scarce and expensive gravel wearing course losses. This aspect was the focus of this exploratory laboratory investigation.

7.2 The Erosion Resistance Test of the CSIR has been refined and clearly has potential to discern between materials in terms of erosion from water flow action.

7.3 A limited sample of gravel wearing course material (granites) was tested as a pilot study in this investigative limited laboratory test program. Nevertheless, materials varied from non-, medium to highly plastic and therefore covering the full spectrum of gravel wearing course material.

7.4 The test results show that Plasticity Index (PI) has a significant effect on resistance to erosion resistance. Low PI's tend to be erosion prone, while the high PI's have better resistance.

7.5 Compactive effort seems to have the strongest effect on erosion resistance, virtually independent of PI. The higher the compactive effort (eg. Closer to 100% Mod AASHTO) the better the erosion resistance.

7.6 An interim tentative design guideline was developed which relates the important factor of compactive effort with erosion gravel loss for a non-, medium and highly plastic (4, 8 and 25) relationships.

7.7 A further refinement of erosion potential zones was proposed to guide decisions regarding the use of chemical stabilisers for erosion prevention.

8. RECOMMENDATIONS

8.1 This initial exploratory study can be expanded to include more material types, such as Shale, Chert, Ferricrete, Diabase etc. as well as the effects of mechanical blending of aggregates.

8.2 Employ all material characterisation aspects (Atterberg limits, OMC, MDD, Grading, Soil PH, Shear strength etc.) and statistically analyse and rate the influence of these variables on erosion for different climatic environments and road alignments.

8.3 Consider the effects of grade (slope gradient and length) versus material characteristics against erosion potential. Flow velocity is a function of grade, which is a function of the detachment and transport of particles and thus erosion potential.

8.4 Full-scale field trails and/or rainfall simulation to quantify the effects of rainfall intensity, rainfall energy and rainfall duration and distribution effects in this controlled environment. Rainfall simulation can also be used to analyse the different components of the road and to quantify the components that is the most erosion sensitive. The performance effects of the shoulders, riding surface, verges etc. can be observed in a controlled environment.

8.5 The CSIR Erosion Resistance testing device can be improved. Actual field sections or the use of rainfall simulators can be employed to improve and calibrate the devise and test method.

8.6 The effect of material characteristics in quantifying erosion potential for the effective use of chemical additives to achieve wearing course performance should be incorporated in further research.

9. ACKNOWLEDGEMENTS

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