Stiffness behaviour of trial road foundations

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ABSTRACT: This paper reports the results of two full-scale field trials to determine the stiffness and density of granular materials receiving different levels of compaction energy and support. The research showed that there were greater improvements in density with initial input of compaction energy, and yet little change in density, but significant increases in stiffness, with the final applications of compaction energy. Density is thus an inappropriate indicator of performance (i.e. resilient elastic stiffness)

1 INTRODUCTION

The road foundation layers, which consist of the capping (where necessary) and sub-base layers that overlie the natural soil subgrade, perform several functions both during construction and when the road is in service. In particular they act as load-spreading layers to reduce to acceptable levels the stresses transmitted to the subgrade, (often) as temporary haul roads during construction, and as construction bases on which the overlying pavement layers can be adequately laid and compacted. The critical loading conditions usually occur during construction where the materials are both directly trafficked and subjected to high levels of compaction energy, i.e. the cases where the stresses are greatest.

Ideally, a fully analytical approach should be adopted for road foundation design. This would require isolation of the critical performance parameters, and a means of measurement of these parameters directly in the laboratory (for design) and in the field (for assurance of adequate construction). It would also require target values to be set, against which the measurements can be judged. The research programme reported herein isolated the critical performance parameters as:

- Resilient elastic modulus (or stiffness)
- Resistance to permanent deformation, which is related to the shear strength of both the component materials and the composite system.

This paper is concerned with the stiffness that can be achieved on site, and the factors that influence it, as part of research to underpin a performance based specification for subgrade and capping.

UK flexible pavement design and construction evolved from a wholly empirical basis to the two-stage semi-empirical approach for the structural design of bituminous pavements given in Transport Research Laboratory Report LR1132 [Powell et al, 1984], which currently forms the basis for design. The first stage concerns the foundation (i.e. construction to top of sub-base), for which an adequate stiffness is a design requirement. LR1132 acknowledges the difficulty of measuring stiffness directly and suggests a means of determining an elastic modulus for subgrade from California Bearing Ratio measurements, although this has been widely criticised. Recent research by the current authors, on behalf of the UK Highways Agency, has shown that laboratory measurement of stiffness remains a challenge, but that major advances have been made in the measurement of stiffness *in situ* and various devices are now available [see Brown et al 1995, Fleming et al 2000].

This paper aims to report the results from two field trials in which road foundations, consisting of a well-graded crushed rock sub-base (termed ‘Type 1’ sub-base in the current UK specifications) overlying different thicknesses of a coarse granular capping, were constructed on relatively soft subgrades. Both density and stiffness were measured at all stages of construction and these were related to the compaction energy applied and the thickness and stiffness of the underlying granular materials. This has enabled the relationship between density and stiffness of the capping and sub-base to be obtained.

2 COMPACTION OF GRANULAR MATERIALS

The stiffness of compacted granular materials is known to vary with the degree of confinement and level of applied stress, and the properties will consequently vary with depth and position relative to an applied load. Determination of stiffness at different positions within a compacted granular layer is practically impossible, but density, which is thought by some to be an indicator of stiffness, can be measured at different depths within a layer using a nuclear density gauge (NDG).

Thom [1988] attributed the density variation within a compacted granular layer to reductions occurring near the surface where there is a lack of confinement and to reductions occurring progressively with depth in the lowermost 40% of the layer where the compaction energy had dissipated. He also showed that lower densities were obtained by compaction onto softer substrates, thus demonstrating that a minimum stiffness of an underlying layer is needed to achieve adequate compaction. This requirement was quantified by Powell et al [1984], who suggested that a stiffness modular ratio of three could be expected between adjacent (competent) layers.

At a more fundamental level, it is known that the degree of compaction, as measured by dry density, of a granular material is dependent on:

- water content, in relation to the optimum water content,
- type of compaction plant and energy input,
- the layer thickness, and thus the distribution of energy with depth, and
- the type of aggregate and its grading.

It is clear that the same factors will control the stiffness of a granular material also, but the correlation between stiffness and dry density is one that is yet to be made in the literature. This is probably due to the lack of a reliable means of assessment of stiffness *in situ* until recently.

3 TRIAL FOUNDATION CONSTRUCTION AND ASSESSMENT

The trial at Bardon Hill Quarry was constructed on a subgrade consisting of soft to firm weathered Mercia Mudstone containing Porphyritic Andesite gravel, a silty clay having a CBR of 1.0-2.5%. Five trial foundations were constructed consisting of 150mm of sub-base overlying 400mm, 300mm, 200mm, 100mm, and no capping. The capping was a Type 6F1 well-graded Porphyritic Andesite and the sub-base was a Type 1 well-graded Porphyritic Andesite, both gradings being in accordance with the UK Specification for Highway Works [SHW, DTp 1993]. Compaction of the capping was effected using three passes of a Benford 1300HV vibrating roller in 100mm layers, while the sub-base was compacted using eight passes of the same roller in one 150mm thick layer (both in accordance with SHW). The water contents of the granular materials were close to, though typically dry of, their optimum values.

The subgrade was excavated in steps immediately prior to the installation of the capping in 100mm thick layers. Testing was carried out on the exposed subgrade, on the surface of the capping after each layer was added, and on the completed sub-base. Stiffness was measured using the TRL Foundation Tester (TFT) and the German Dynamic Plate Test (GDP) at a minimum of six points for each bay during capping construction and at nine points on the completed capping. Similarly, stiffness testing was carried out at six points on the sub-base after two and four passes of the compactor and at nine points on the completed sub-base. Details of the devices for measuring stiffness are given elsewhere [Rogers 1995, Fleming et al 2000]. The density was measured using a NDG in direct transmission mode at a minimum of six points in each bay (corresponding with the stiffness measurements) after completion of the capping and the sub-base. Density was also measured after different levels of compaction of the thickest capping (1, 2 and 3 roller passes) and the sub-base (2, 4 and 8 roller passes).

The trial at Mountsorrel Quarry was constructed on a stiff weathered Mercia Mudstone subgrade (c_u~100kPa, CBR~3.5-9.0%), the silty clay containing occasional granodiorite gravel that became more prevalent with depth. Three trial foundations were constructed consisting of 150mm of sub-base overlying 450mm, 300mm and 150mm of capping. The capping was a 40mm down screened 'crusher run' granodiorite which lacked sufficient fines to be classified as Type 6F1 and the sub-base was a Type 1 well-graded granodiorite. Compaction of both the capping and sub-base was effected using five passes of a Benford SP2010 vibrating roller in 150mm thick layers (in accordance with SHW). The water contents of the granular materials were again close to, but dry of, their optimum values.

The construction and testing procedures were similar to those described above for the Bardon site. Stiffness was measured using the GDP at a minimum of eight points for each bay during capping construction, and at twelve points using both the GDP and the Falling Weight Deflectometer (FWD) on the completed capping. Similarly, stiffness testing was carried out at eight points on the sub-base after one and two passes of the compactor and at twelve points on the completed sub-base. The density was measured using a NDG in direct transmission mode at twelve points in each bay, to correspond with the stiffness measurements, after completion of the capping and the sub-base. Additional readings were taken after one and two roller passes during construction of the final layer of capping and the sub-base. Interestingly, some of the GDP readings were found to be affected by the magnetic field generated by high-voltage overhead power lines at one end of the trial.

4 TEST RESULTS

Selected results will be presented to illustrate the relationships between the compaction energy, the support of underlying layers, and the stiffness and density of the capping and sub-base.

The relationship between the dry density of the sub-base and compaction energy at Mountsorrel is illustrated in Figure 1. The general trend was as expected, the density after one pass of the roller being significantly less than that after two passes and with (generally) some further improvement after five passes according to the law of diminishing returns. If a target dry density of 97% of the maximum modified AASHTO value (i.e. 4.5 kg hammer test) is adopted, all foundations achieved this value (1.94 Mg/m^3) after five passes.

Since the clay subgrade was expected to be less stiff than a compacted granular capping layer, it would be expected that density would become progressively greater (for any one level of compaction energy) as the thickness of capping increased. This was not, however, found to be the case. What can be concluded from these results, however, is that the density reached a consistent value after five passes of the roller.

The overall behaviour here was attributed to the fact that the subgrade was relatively competent and that there will inevitably be variations in the properties of compacted granular materials. The fact that the densities at the end of the compaction process were almost identical indicated that the SHW requirement for five passes of the roller yielded the required result as far as density is concerned, i.e. a uniform final product.

Figure 2 shows the equivalent relationship between the dry density of sub-base and compaction energy at Bardon. In this case the subgrade was far softer. All of the sub-bases again showed the expected increase in density with compaction energy, with the density increasing for two to four and four to eight passes of the roller in all cases. The possible target value of 97% of the modified AASHTO maximum dry density (2.015 Mg/m^3) was reached in all bays after four passes of the roller.

The densities followed a generally consistent pattern with the exception of the sub-base constructed without capping. The densities after two passes of the roller were remarkably similar, while those after four passes showed an increase with thickness of underlying capping. After eight passes of the roller, the sub-base on 400mm of capping showed significant further improvement, whereas the densities on the thinner capping layers reached a consistent value. Where no capping was placed, the density achieved in the sub-base was only marginally lower than that achieved on the thickest capping.

This behaviour was attributed to a locally competent section subgrade beneath the sub-base constructed without capping. It was equally evident from the site that the densities of the first layer of capping elsewhere (i.e. where the subgrade was less competent) were lower and in accordance with the patterns shown in the other foundations.

The same data are shown in the relationship between dry density of sub-base and thickness of supporting capping at Bardon in Figure 3. This shows more graphically the relative insensitivity of the thickness of the underlying capping, whereas the improvement in density with compaction energy is clearly evident, in spite of the considerable scatter in the data shown by the error bands.

The relationship between stiffness of the sub-base, as measured by the FWD, and thickness of supporting capping at Mountsorrel is shown in Figure 4. This demonstrates that there was a consistent pattern of improvement in stiffness with both capping thickness and compaction energy. However, the improvement in stiffness between one and two passes of the roller is much lower than that between two and five passes. This is the opposite of the pattern shown by the density change, in which the final three passes had much less effect than the second. It is also apparent that increasing capping thickness had the expected influence of improved stiffness as the influence of the subgrade diminished, whereas the density data did not follow a well-defined pattern. For example, there was no indication that the greatest density after two passes of the roller for the sub-base on 300mm of capping produced a greater stiffness.

The equivalent stiffness data for Bardon, albeit that they were obtained using the TFT and GDP, are shown in Figures 5 and 6 respectively. The TFT data show that the trend of increasing stiffness with compaction energy, although not quite as well defined as at Mountsorrel, is still apparent. In this case, however, four passes of the roller produced a stiffness that was close to that of eight passes. The trend of a marginal increase only in stiffness between the sub-bases underlain by no capping and 100mm of capping, followed by significant increases for progressively thicker capping that tail off as the thickest layer is reached, was as might be expected. These data therefore indicated that the TFT was able to discern sensitively the true behaviour of the foundations.

The stiffness data measured by the GDP were apparently less sensitive to the foundation performance. There was virtually no difference between the stiffnesses for different compaction energies and less sensitivity to the expected trend of marginal increase from 0 to 100mm of capping.

The relationship between the dry density of the surface layer of capping and the stiffness of the supporting capping at Mountsorrel is shown in Figure 7. It should be noted that the two devices measure stiffnesses under different applied stress regimes, and thus their zones of influence will lead to different absolute measurements. It is clear, however, that, regardless of the device used, there is virtually no correlation between density achieved and stiffness of the underlying support. This finding is reinforced by the measurements on the sub-base at Bardon (Figure 8) which, although showing some increase for the stiffest capping layers, nevertheless shows that this effect is small in relation to the error bands.

4 CONCLUSIONS

The general model of granular material improvement by compaction, deriving from the research, is one of:

- greater improvements in density by the initial input of compaction energy (i.e. by the first passes of the roller), but of
- significant improvements in stiffness resulting from the later passes of the roller as the structure readjusts to resist most effectively the compaction forces.

Although the stiffness will necessarily increase during the initial compaction passes, adequate stiffness development can only take place once a density close to its maximum for the water content concerned has been reached. Once this level of density has been reached, the enhanced stiffness is developed as a result of local reorientation of particles yielding a greater number of point contacts and, importantly, an increase in ‘locked-in’ stresses which result in greater confinement and thus greater stiffness.

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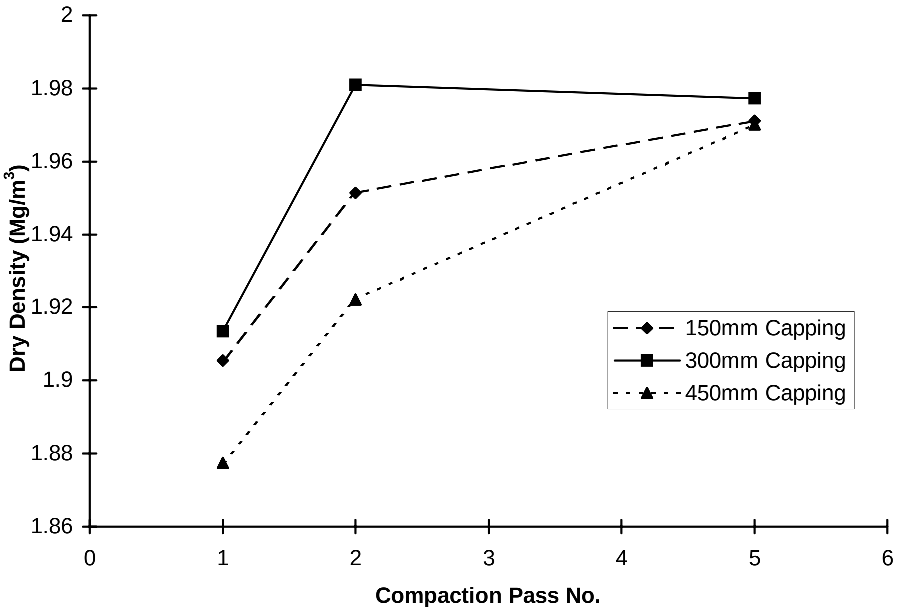

Figure 1. Relationship between Dry Density of Sub-Base and Compaction Energy at Mountsorrel

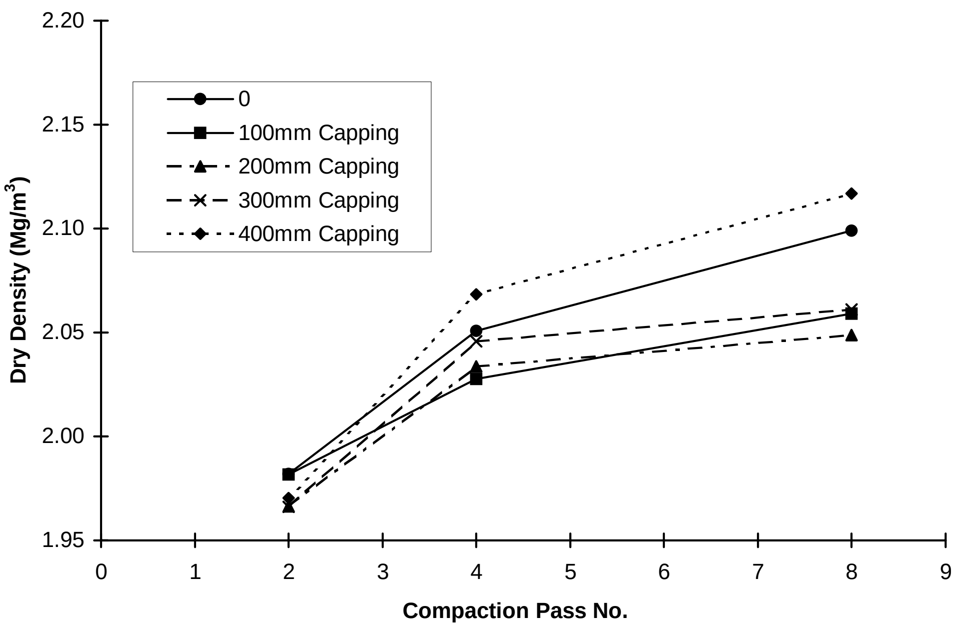

Figure 2. Relationship between Dry Density of Sub-Base and Compaction Energy at Bardon

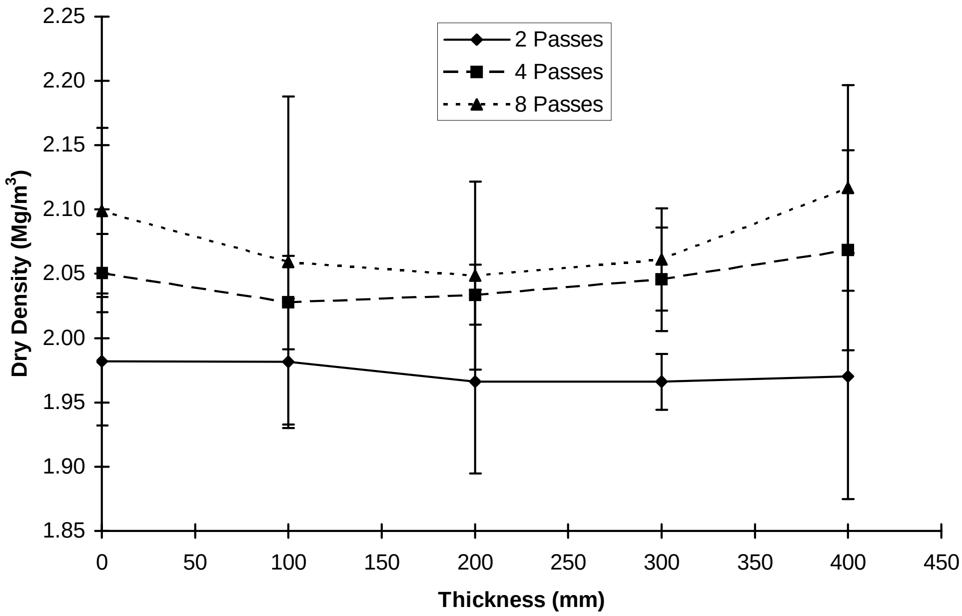

Figure 3. Relationship between Dry Density of Sub-Base and Thickness of Supporting Capping at Bardon

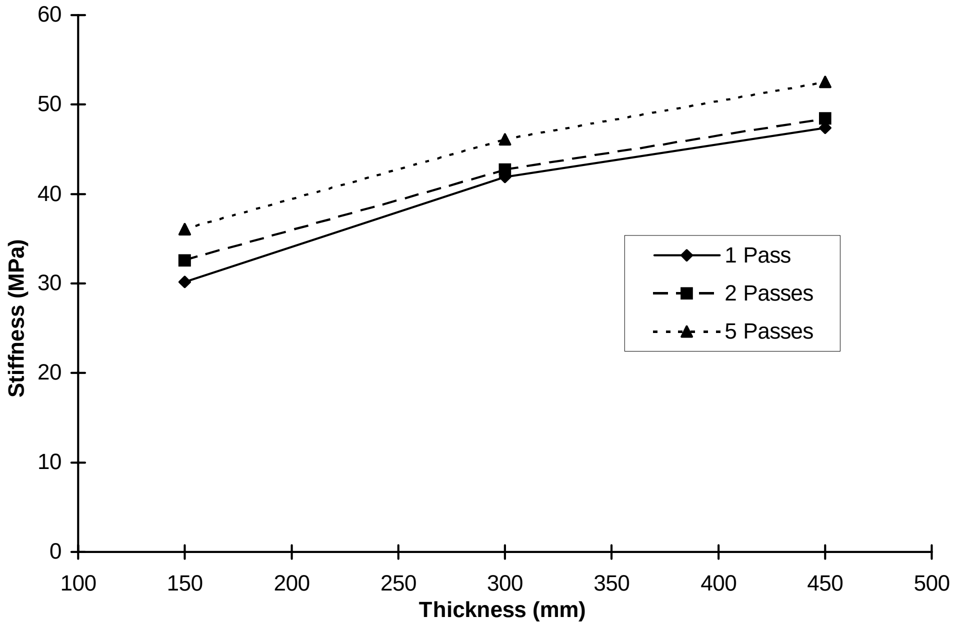

Figure 4. Relationship between FWD Stiffness of Sub-Base and Thickness of Supporting Capping at Mountsorrel

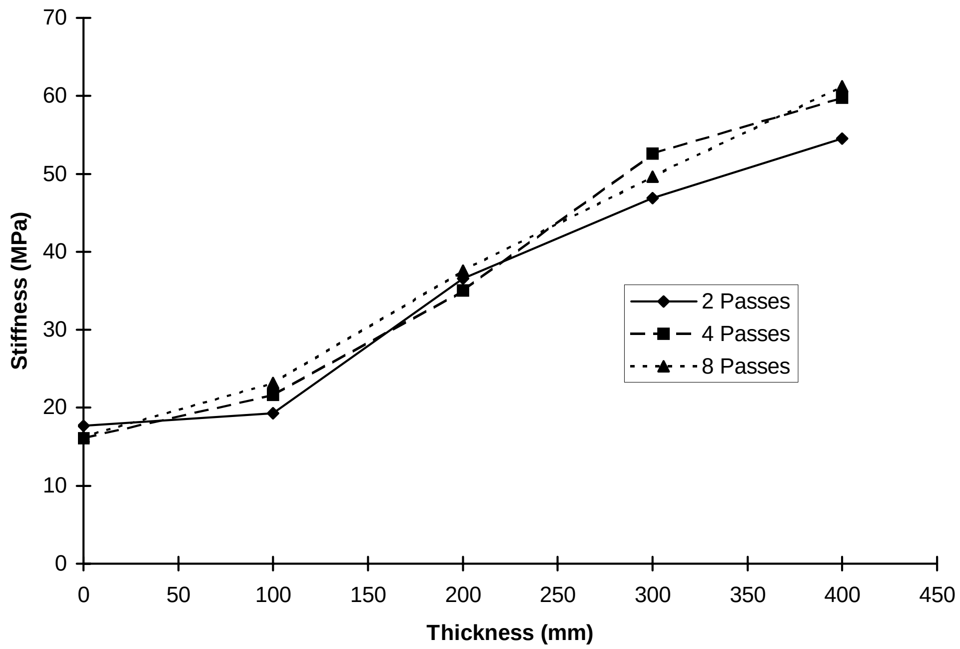

Figure 5. Relationship between TFT Stiffness of Sub-Base and Thickness of Supporting Capping at Bardon

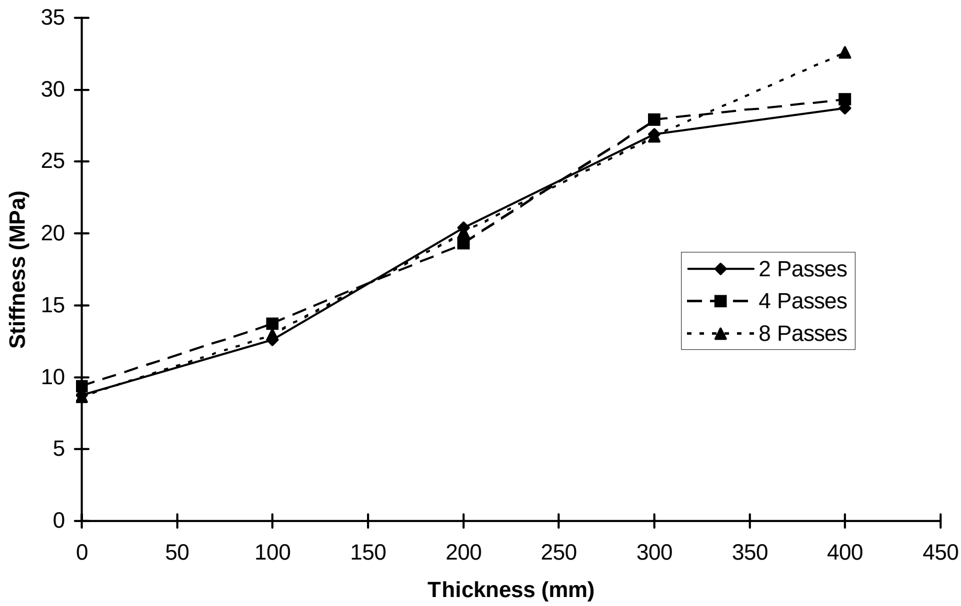

Figure 6. Relationship between GDP Stiffness of Sub-Base and Thickness of Supporting Capping at Bardon

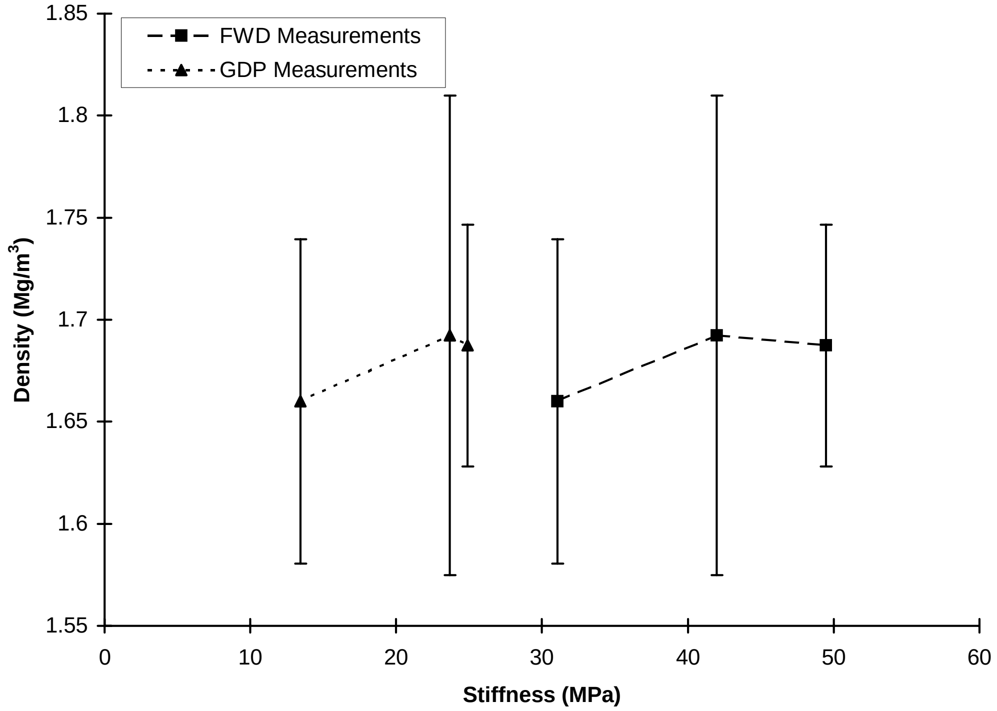

Figure 7. Relationship between Dry Density of Surface of Capping and Stiffness of Supporting Capping at Mountsorrel

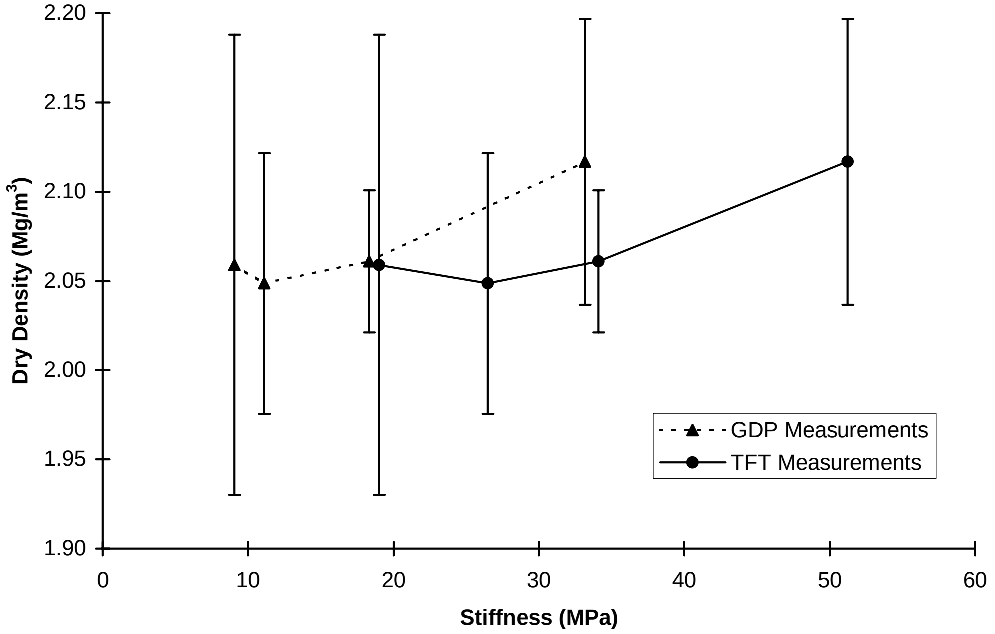

Figure 8. Relationship between Dry Density of Sub-Base and Stiffness of Supporting Capping at Bardon