
Effects of Gradation, Moisture and Density on Strength, Stiffness and Deformation Resistance of Pure Crushed Stone Base Blend

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Abstract

This paper investigates the effect of some physical properties on strength, stiffness, and deformation resistance of pure dense well graded crushed stone base blends. Manufactured crushed basaltic stone of three different particle sizes from Jebel Touryia was adopted for this study. Initially, attempt was performed to produce number of base blends from mixing these crushed particle sizes. Only two base blends are found to satisfy TRL GB3 base gradation requirements. An experimental testing program involves sieve, compaction, Resilient Modulus (M_R) and Permanent Deformation (PD) was conducted on the two considered blends. From tests results it is observed that M_R decreased and permanent deformation increased when the moisture content is less than optimum. The same applies when moisture content higher than optimum. In the first case there is less water i.e less lubricant which is important for particles interlocking on compaction. In the other case much water causes water pore pressure which reduces effective pressure on compaction. At optimum blends achieved maximum dry density and then gave high M_R values and low PD value.

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Generally it can be concluded that gradation, moisture and density have great influence on strength, stiffness and deformation resistance of pure dense well graded base blend.

Keywords: crushed stone; blend; compaction; resilient modulus; permanent deformation.

1.0 Introduction

Well graded dense pure crushed stone is widely recommended as road and airport runway base course materials for its excellent carrying capacity features under different types and magnitudes of repeated loads. Some fundamental factors such as; crushed mix gradation, moisture and density has significant influences on the strength, stiffness and deformation resistance of these typical base materials. Khartoum State blessed with variety of natural open quarries that possess different types of natural unbound gravelly road materials; these natural gravels are predominantly satisfying sub base requirements but rarely may realize base ones. Some volcanic eruptions in the past had resulted in forming some Outcropping Mountains which are composed of granite and basaltic rock types. These mountains are located north, north-west and south-west of Khartoum.

Numbers of crushing plants are mounted there for crushing the required sizes used in road as well as runway construction use, the manufactured crushed stone are satisfying AASHTO and Transport Research Laboratory of United Kingdom (TRL) base course gradation and strength requirements. Plate 1 shows the three different sizes that were produced from Jebel Touryia south –west Khartoum. The exercise of using the crushed stone as base material is lately practiced in pavement construction in Sudan. The main objective of the study is to identify the effect of gradation, density and moisture on the strength, stiffness and deformation resistance of well graded dense pure crushed stone base course material.



Plate1:Three Different Sizes of Crushed Basaltic Stone Product from Jebel Touryia

2.0 Literature Review

Transport Research Laboratory (TRL) of UK [1] specified two types for graded screened crushed stone

roadbase material: GB1, A that concerns with fresh un-weathered crushed stone of non-plastic parent fines and GB1, B which regards crushed rock, gravel or boulders with plasticity index (PI) < 6 for the composed soil or parent fines.

The authors in [2,3,4,5,6,7,8] noted that crushed aggregates having angular to sub-angular shaped particles provide better load spreading and higher resilient moduli than uncrushed gravels with round surfaces. The deformation response of unbound granular materials under repeated, traffic-type loading is defined by a resilient response, which is important for the load-carrying ability of the pavement and a permanent strain response, which characterizes the long-term performance of the pavement and the rutting phenomenon [9]. Lekarp et al. [9] suggested that the crushed stone, angular materials undergo smaller permanent deformation compared to materials such as gravel with rounded grain.

The authors in [10,11] found that uniformly graded aggregates were slightly stiffer than well-graded aggregates. Kolisoja [12] showed that the resilient modulus increases with increasing maximum particle size. Well graded material can achieve higher densities lead to higher stiffness [13]. Gray [14] noted that for a dense-graded crushed aggregate base material having a 25-mm top size, maximum strength is achieved at a fines content of about 8%. Hicks and Monismith [2] studied and reported that the resilient modulus decreased for partially crushed aggregates with an increase in the fines content whereas, the resilient modulus increased for crushed aggregates with an increase in the fines content.

The authors in [3,15] reported that for crushed stone, angular materials undergo smaller permanent deformation compared to materials such as gravel with rounded grain. This behavior was said to be a result of a higher angle of shear resistance in angular materials due to better particle interlock. The authors in [16] clarified that the effect of material grading on permanent deformation to be more significant than the degree of compaction (density) with the highest plastic strain resistance for the densest mix.

The authors in [17] observed that the effect of the degree of compaction is more important for crushed coarse material than the natural materials. He concluded that the crushed rock materials needed more compaction. Hicks and Monismith [2] found that the effect of density to be greater for partially crushed than for fully crushed aggregates. They noted that the resilient modulus increased with relative density for the partially crushed aggregate tested whereas it remained almost unchanged when the aggregate was fully crushed. They further reported that the significance of changes in density decreased as the fines content of the granular material increased.

One of the key environmental factors is water. Water in a pavement has its origin from many sources, either the specified quantity with the unbound layers upon construction (OMC), groundwater, surface water mitigating through the shoulder, ditches or imbibing through in the paved surface of the pavement.

The authors in [18,19] reported that too much water trapped in the pavement structure combined with the repeated loading from traffic may cause decrease in effective stress and due to excessive pore pressure occurrence in the material. The consequence is reduction in bearing capacity in the base and subbase leading to cracking and rutting of the asphalt pavement.

The moisture content of most untreated granular materials has been found to affect the resilient response characteristics of the material in laboratory and in situ conditions [20]. Thom and Brown [5] reported that increased moisture content may decrease the resilient modulus of a wet aggregate base material to approximately 10% of the value corresponding to the dry condition.

The authors in [21,19,22] comprehensively studied the resilient behavior of granular materials and all agreed that samples compacted at moisture higher than the optimum moisture contents had greater resilient and permanent deformations than those compacted at moisture lower than the optimum moisture contents.

in [19]; and through experimental exercises found that the resilient modulus tends to increase with the increasing moisture content up to the optimum moisture content due to the development of suction. Beyond the optimum moisture content, the resilient modulus decreases with increasing moisture content due to the development of excess pore water pressure. The effect changes to the opposite and stiffness starts to decline fairly rapidly. As moisture content increases and saturation is approached, positive pore pressure may develop under rapid applied loads.

Researchers who studied the behavior of granular materials at high degrees of saturation have all reported a notable dependence of resilient modulus on moisture content, with the modulus decreasing with growing saturation level [13].

The existent of water in the material can both have positive and negative effect on the permanent deformation. An adequate amount of water has positive effect on the strength and the stress and strain behavior of the unbound granular material [23]. On the other hand, high water content causes excessive pore pressure, which in it turns leads to a reduction in stiffness and hence increased permanent deformation. Barksdale [24] demonstrated that excessive pore pressure reduces the effective stress, resulting in diminishing permanent deformation resistance of the material.

The authors in [16] explained that under repeated stresses from traffic load, the water between the particles become pressurized and the pore pressure counteract the stresses, which is pushing the particles together.

The authors in [25] reported from the permanent deformation results that measured by repeated load triaxial tests on the crushed stone at varying degrees of saturation. In all cases, the samples experienced a substantial increase in permanent deformation after soaking. It was suggested that one reason for the observed increase

was development of transient pore pressures in the soaked samples. Holubec [26] monitored from tests performed on granular material that an increase of the water content from 3.1 per cent to 5.7 per cent results in an increase of the total axial strain by 300 per cent.

3. Materials and Test Methods

The main objective of this study is to identify the effect of gradation, density and moisture on the strength, stiffness and deformation resistance of well graded dense crushed stone base material blends.

There are number of stone crushing plants in Khartoum State for manufacturing different cube-shaped particle sizes from variety of stone types such as basalt and granite. Generally, most of crushed stone from different stone sources in Khartoum state are complying with the base specifications required in Sudan. In this investigation; the material that adopted is basaltic crushed stone provided from Jebel Touryia (west of Khartoum) which comprises three different sizes{(19-12mm), (12-5 mm), (5-0mm)} as shown in Plate 1. Jebel Touryia is one of several small out crops of Basalt cutting Omdurman Formation near Omdurman City [27], which is originally from the tertiary volcanic [28].

Comprehensive laboratory testing program was performed on the selected crushed stone includes; grain size distribution, moisture content, compaction, resilient modulus and permanent deformation tests. These tests were carried out according to AASHTO and TRL tests procedures.

From successive blending attempts on the given three sizes of crushed stone two were found to fit well with TRL GB1 base gradation [1], namely blend1 composed of (50.3%+22.4%+27.3%) and blend 2 composed of (52%+16.2%+31.8%) as given in Figure 1 and Table 1.

4. Tests and Results

Results for different laboratory tests that were carried out on the two crushed stone base blends in the investigation are given here-after; Grain size distribution for the two adopted pure crushed stone compared to the TRL GB1 base gradation is presented in Figure 1 and demonstrated in Table 1.

The two blends were subjected to moisture content test which resulted in 0.781% primary moisture content for blend1 and 0.8648% for blend2.

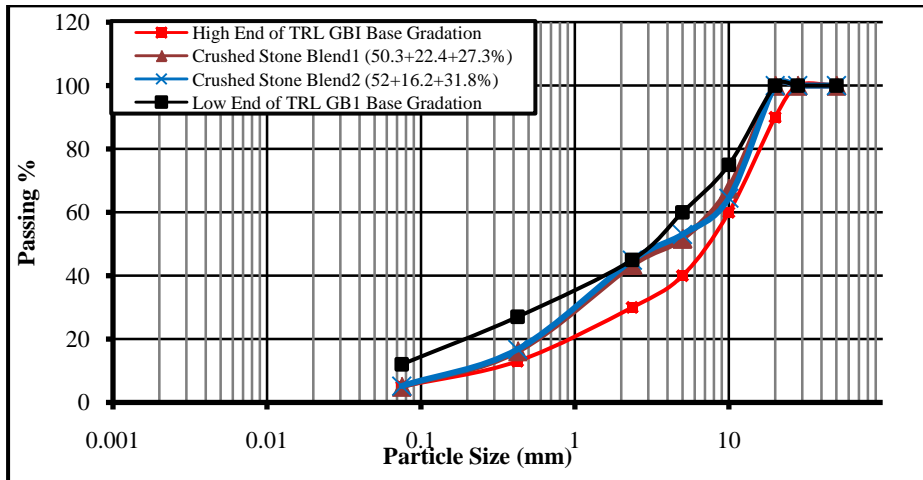


Fig.1: Grain Size Distribution for The Two Pure Crushed Stone Base Blends (TRL Gradation)

Table 1: Gradation of the Two Crushed Base Blends

BS test sieve	TRL GB1 Gradation Requirements		Test Results	
	Minimum	Maximum	Blend1	Blend2
	% Passing	% Passing		
50	100	100	100	100
28	100	100	100	100
20	90	100	100	100
10	60	75	67.55	64.474
5	40	60	51.69	53
2.36	30	45	43.43	44.897
0.425	13	27	16.207	16.75
0.075	5	12	5.01	5.17

Initially, a series of compaction test trials were carried out on blend2 using vibratory compacter and the resilient modulus mold (300 mm height & 150 mm diameter) to adopt the relative OMC that results in higher bulk unit and consequently determines the maximum dry density (MDD), these parameters were successfully achieved by adding 340 ml of water to the specified weight of crushed stone blend2 (12 kg) within which no particles segregation was developed and the measured MDD equals 2.2379 gm./cm³. The same exercise was then performed on blend1 by adding the same 340 ml of water and compacted following

the same process (operator, environment, compaction rate and effort) that used for blend2; the measured MDD for blend1 was found to be 2.2073 gm./cm³. This decrease in MDD might be attributed to the influence of the different gradation used or caused by the occurrence of pore water pressure from the excess water than that needed as OMC for blend1. Another specimen from blend1+340 ml was reconstituted and was subjected to higher compaction effort using the same vibratory compactor to give a dry density=2.2244 gm./cm³ which is closed to or equals the maximum dry density of blend2. It seemed to be that, the top half of the prepared specimen which is directly affected by the high vibration pluses from the high compaction effort might be strongly interlocked the reconstituted particles consequently enforced the excess water to move towards the bottom of the specimen. The lower half of the specimen is also was compacted but might not reached the upper half level due to the development of pore water pressure. The advanced laboratory apparatus that used in this work are shown in Plates 2, 3, and 4. The resilient modulus test results for the two blends at different densities are given in figure (2-a/b), whereas resilient modulus test sequences values for blend1 at different moisture contents are shown in Figure (3-a/b).



Plate 2: Vibratory Hammer



Plate 3: Compacting the layer with vibratory compactor

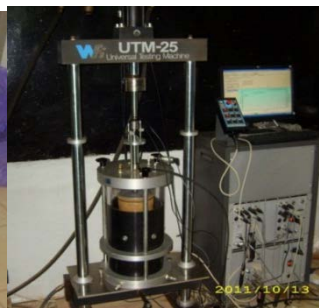


Plate 4: UTM-25 Cyclic Triaxial set-ups for Resilient Modulus & Permanent Deformation Tests

Table 2 gives the permanent deformation test results for the blend1 at different moisture contents and Figure 4 displays the effect of moisture content variations and their corresponding maximum dry densities on the resulted permanent deformation values for the base blend1.

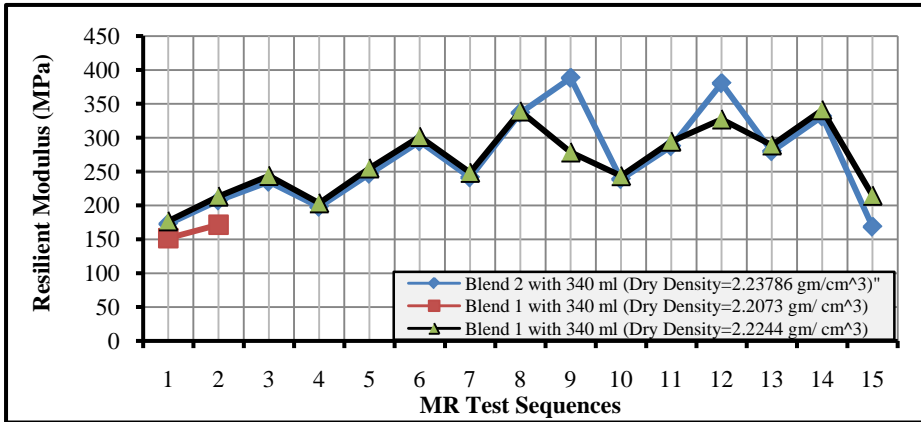


Fig.2-a: Resilient Modulus for the Two Blends at Different Densities with 340 ml M.C
(M_R Values with Test's Sequences)

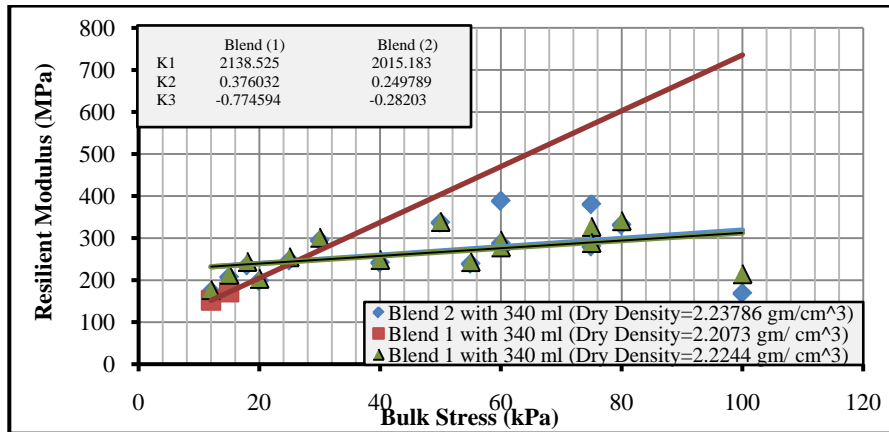


Fig. 2-b: Resilient Modulus for the Two Blends at Different Densities with 340 ml M.C
(M_R Values versus Bulk stress {kPa})

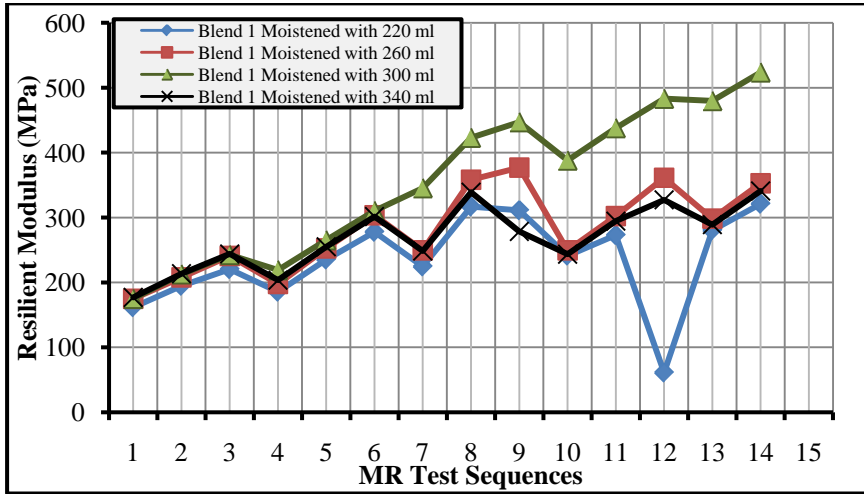


Fig. 3-a: Resilient Modulus Values Blend1 at Different Moisture Contents with 220, 260, 300 & 340 ml

(M_R Values with Test's Sequences)

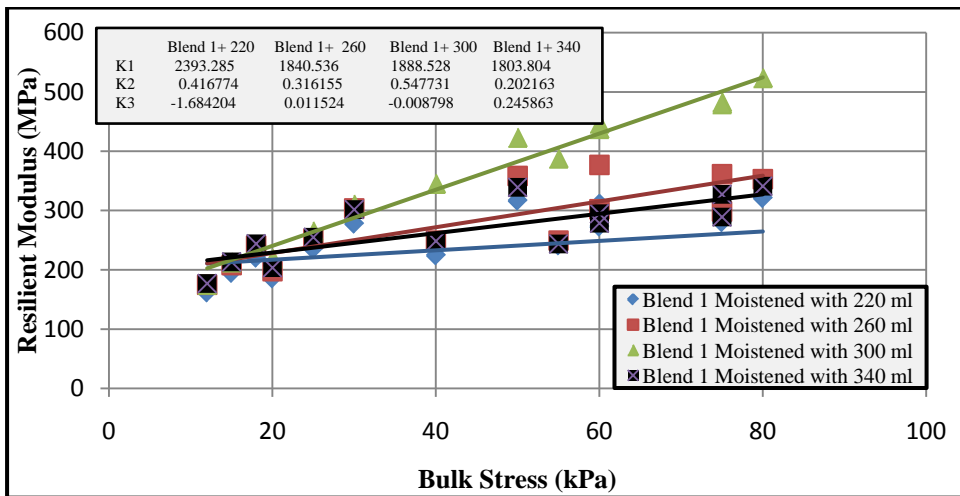


Fig. 3-b: Resilient Modulus Values for Blend1 at Different Moisture Contents with 220, 260, 300 & 340 ml

(M_R Values versus Bulk stress {kPa})

Table 2: Permanent Deformation Results for Base Blend2 Watered at Variable Moisture Contents

Type of Blend Specimen	Permanent Deformation (mm)
Blend1 Watered with 220 ml	0.0057814
Blend1 Watered with 260 ml	0.001347
Blend1 Watered with 300 ml	0.0027
Blend1 Watered with 340 ml	0.006

5. Results Analysis and Discussions

*The gradation curves for the two adopted crushed base blends fall within the TRL GB1 base gradation envelope. Both curves plot close to the low end of TRL GB1 gradation at sieve 2.36 mm and almost coincide with the high end of TRL GB1 gradation at sieve 0.075 mm.

* The existing moisture content of the two blends was 0.781% and 0.8648% for blend1 and blend2 respectively. The higher moisture content of blend2 due to the fact that blend2 possesses large quantity of rock dust (31.8%) which resulted in greater surface area compared to blend1, this lead to high moisture content absorption.

* From the results of resilient modulus test for the three prepared specimens blend2+340 ml [MDD=2.2379 gm./mm³], blend1+340 ml [MDD=2.2073 gm./cm³] and blend1+340 ml [MDD=2.2244 gm./mm³] which are presented in Figure (2-a/b), it is observed that upon M_R testing process of blend1 of 2.2073 gm./mm³ dry density (wet of optimum moisture), the excess water caused the particles to slide, slip over each other and segregate in terms of lack of bond between particles, and that led the sample to collapse under the high deviator stress that subjected from the third sequence (69 kPa). By increasing the compaction effort for another similar blend1 specimen, the resulted M_R values are generally equal to that obtained by blend2.

* Both blends blend1 and blend2 are satisfying the TRL GB1 base gradation specifications but blend1 gradation is the most closer to the middle range of the given gradation as shown Figure 1 and Table 1.

*Resilient modulus as depicted in Figure (2-a/b) was approximately the same for both blends although blend1 (2.2244 gm./mm³) was prepared at moisture content wetter than its optimum moisture content (development of pore water pressure) unlike blend2 which was prepared at its OMC. Therefore blend1 can be selected as ideal blend to be used further for studying the effect of moisture variation on density, stiffness and deformation resistance of the dense well graded crushed stone base material.

. *Blend1 + 220 ml of water measured the lowest M_R sequence values, whereas blend1+300 ml achieved the highest M_R values. The two remaining samples (blend1+260 ml & blend1+340 ml) obtained M_R values in between but the four samples satisfy the required base M_R values as shown in Figure (3-a/b).

*The permanent deformation (PD) test was carried out on the adopted crushed blend1 with the same different moistures that used in resilient modulus tests; blend 1+220 ml, +260, +300 and +340 ml. It is observed that blend1+260 ml measured the lowest PD value (0.001347 mm) compared to the other specimens as given in Table 2.

Figure 4 presents the influence of two parameters; moisture content% and density on the resulted permanent deformation for blend1. It is observed that as the moisture content increases and moves close (from dry to optimum) to OMC the corresponding dry density increases towards Maximum Dry density (MDD) and consequently permanent deformation value decreases. At optimum moisture content (blend1+260 ml) the respective dry unit achieved MDD and measured the lowest permanent deformation value compared to the other specimens in this exercise.

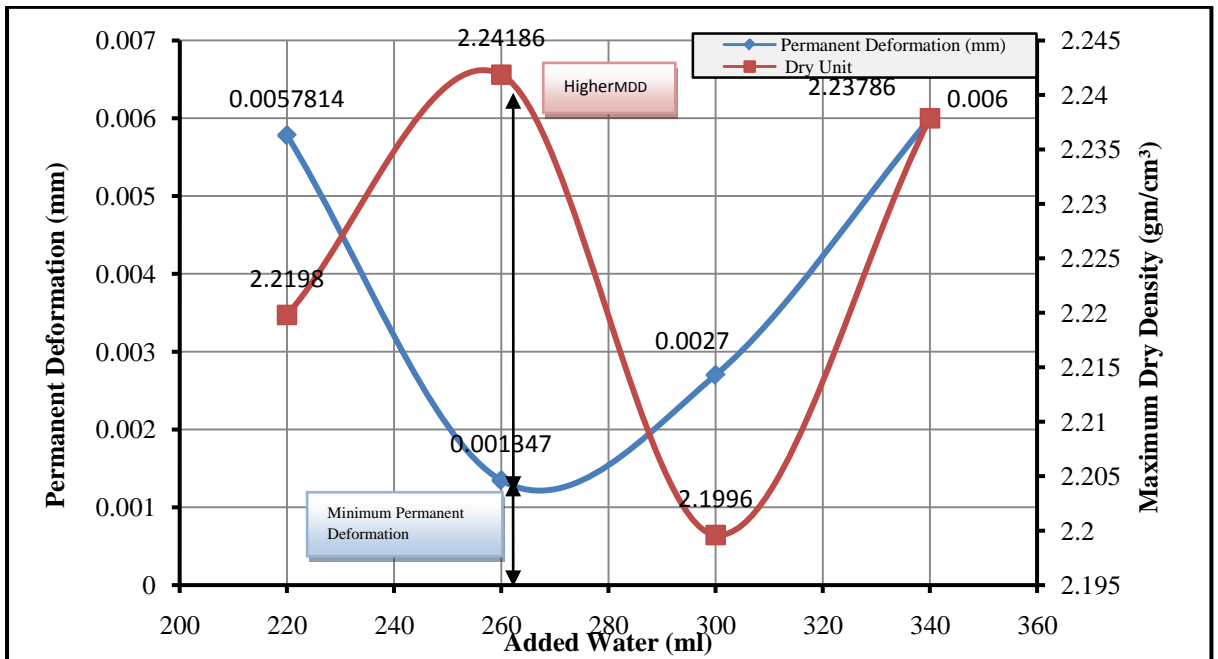


Fig. 4: Correlation between PD, Moisture Content% and Dry Density for the Blend1

6. Conclusions

In order to achieve the objective of the study, several tests as outlined previously were conducted. The outcome of this study is as follows:

- Through blending exercise on the three produced crushed stones sizes, only two blends blend1 and blend2 were found to satisfy the required TRL GB1 base gradation. On the other hand blend1 possesses the less particles surface area compared to blend2.
- It was observed that the two crushed base blends when compacted at different densities measured resilient modulus values that satisfied base stiffness requirements.
- Since the achieved densities were equated for the two well graded crushed base blends (1&2) by controlling the compaction energy, both approximately gave same average resilient modulus values although blend1 possessed the less particles surface area.
- The excess water that was used to lubricate blend1 (blend1+340 ml) when molded to normal compaction energy resulted in the development of pore water pressure, facilitated the particles movement and segregation within the specimen consequently led it to its collapse during resilient modulus test.
- It was observed that the crushed base blend1+220 ml (dry of optimum) obtained the lowest M_R values of all samples in the investigation and that attributed to the limited lubricant (moisture content) that assists the interlocking of the particles during compaction process.
- The development of pore water pressure in unbound material will result in improper mechanistic-empirical design parameters such as resilient modulus and permanent deformation and their use may mislead to inadequate design results.
- It was found that blend1 when wetted at OMC (blend1+260 ml) experienced high deformation resistance and gave the lowest permanent deformation value of all samples in question.
- It was proved that the well graded dense crushed stone base material can measure high stiffness permanent deformation resistance values when wetted at OMC and compacted to MDD.
- Although resilient modulus and the permanent deformation are cyclic (dynamic) test results, both are stress dependent, both might share the factors that affecting their responses such as stress, moisture content, gradation ...etc., but at different levels. It could be noticed that it will be more complex and difficult to correlate M_R and PD values for the same unbound material. Physically their behaviours are quite different because M_R value depends on the magnitude of the resilient strain whereas PD is the plastic strain dependent
- In general, it was found that gradation, moisture, density and fines content have great influence on engineering properties, strength, stiffness and deformation resistance of pure dense well graded base blend.
- Generally it can be concluded that gradation, moisture and density have great influence on strength, stiffness and deformation resistance of pure dense well graded base blend.

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