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USING TUFF AND LIMESTONE SAND TO MINIMIZE WATER CONSUMPTION OF PAVEMENT CONSTRUCTION IN ARID REGIONS

Abdelhamid MAMMERI[1], Mostefa LALLAM[1,2], Salah Eddine GUELLATI[3], Mohsen SHAMSAEI[4,*]

[1] Laboratory Mechanics of Structures, University of Tahri Mohamed, Béchar 08000, Algeria.
[2] Department of Civil Engineering, Faculty of Sciences and Technology, University of Mascara, Mascara 29000, Algeria.
[3] Central Public Works Laboratory, 1 rue Rahim Kaddour Hussein Dey, Alger 16000. Algeria.
[4] Ph.D. Candidate, Department of Construction Engineering, École de Technologie Superieure, Montreal, Canada.
[*] corresponding author: mohsen.shamsaei.1@ens.etsmtl.ca

Abstract

Soil compaction is a significant parameter for road construction projects. Since materials and soil compaction play important roles in the stability and durability of roads. This study focuses on the importance of the problems related to water resources in arid regions, considering both the economy and the population in these areas. For this reason, the local materials in Bechar (Algeria) were used to enhance the road construction process. Hence, using the combination of tuff and limestone sand (LS) materials to minimize the amount of water for the road construction compaction is investigated. Different combinations, including 100% tuff, 80% tuff and 20% limestone sand, 70% tuff and 30% limestone sand, and 60% tuff and 40% limestone sand, were evaluated with the Proctor and California Bearing Ratio (CBR) tests. The test results showed that using 60% tuff and 40% limestone sand resulted in the minimum water content of 10.5% compared to other combinations of tuff and limestone sand of this study, and it will be beneficial in arid regions where there is a water shortage. Three different percentages of lime (1%,2%, and 3%) were also added to the optimum mixture. However, the results showed that adding this material has no significant mechanical effects.

Keywords:

Road Construction;
Compaction Methods;
Tuff and limestone Sand;
Arid Regions;
Water Conservation.

1 Introduction

Compaction irregularities in the subgrade soil are one of the primary causes of road failures. Hence, soil compaction has been used to improve the quality of pavements in different ways. Two significant developments have solved this problem, including the California Bearing Ratio (CBR) and Proctor compaction curves [1, 2]. The specification of soil compaction is of major significance for construction projects. For instance, the minimum dry density should be 95% of modified Proctor or Proctor methods [3]. In addition to these tests, some non-destructive methods can be used for pavement evaluation, such as ground penetrating radar (GPR) and static load test (SLT) [4, 5]. Despite these introduced methods, some materials were used to evaluate the soil properties after compaction. Maximum dry bulk density (MDBD) and critical moisture content (CMC) were investigated after using three organic materials, including peat, farm yard manure (FYM), and filter press mud (FPM) in sandy loam and clay soils. These soils were compacted at different moisture contents, and the result showed that using these materials decreased the MDBD by around 16 %. However, the CMC was increased by around 10% after using these organic materials [6].

Using waste materials for road construction has grabbed researchers' attention in recent years, and an array of waste materials, including polyethylene cross-linked, ceramic, coal, brick, concrete, and glass have been used for road construction [7–13]. For instance, one of these materials which was used in cement-stabilized soil was waste rubber. One important reason for using this material was to increase the tensile strength of this type of soil which is used in rural areas in developing countries. The rubber was used up to 30% by weight, and indirect tensile strength (ITS), compressive strength (UCS), and indirect tensile fatigue life (NF) tests were performed. The test results indicated that the capacity of these roads to withstand the plastic strain against fatigue was improved [14, 15].

Moisture content is one of the most important elements in soil compaction. In order to measure the optimum moisture content (OMC) at which soil can achieve maximum dry unit weights or densities, normal or modified Proctor (compaction) tests are commonly used. Before placing layers at the top of the compacted soil, the degree of saturation may have a limit, depending on the dry density and moisture content. High moisture content can result in a high saturation degree which can be more than the optimum water content, resulting in lower density and strength. Hence, the saturation degree for roads should be less than 70% [3]. Moreover, the compacting of soil fill material plays a vital role in stabilizing some structures such as highway embankments and it has a direct impact on the load transfer efficiency of pavements [16–18]. Hence, the effect of using some materials on the OMC was evaluated in some studies. Municipal incinerated bottom ash (MIBA) was one of these materials used as an unbound material for road applications. Using up to 100 % (by weight) of MIBA changed the OMC and maximum dry density from 5.6% and 2410 kg/m^3 to 11.5% and 1890 kg/m^3, respectively, which is attributed to its mineral compositions [19]. Besides, the mineral compositions of pavement materials affect the thermal conduction and aggregate-bitumen adhesion [20, 21].

The Sahara Desert covers more than three-quarters of the Algerian territory. The ideas and principles of road construction in the Sahara have been developed since the mid-1950s. In the southern parts of the country, particularly in the Bechar region, limestone crusts are among the locally widespread materials used extensively as embankments and road construction materials. Due to water scarcity in these regions, the compaction process is costly and difficult. As the water sources are very far from the road construction projects (about 100 to 300 km), the compaction operations (drilling wells, pumping water, distributing, mixing) sometimes necessitate a restrictive site organization, especially intending to limit the rapid evaporation of water into the atmosphere. Former projects have demonstrated that the cost of water required to compact materials can cover up to a third of the cost price of road infrastructure [22].

Few studies have suggested the possibility of compacting soils in arid regions to much lower than optimum water content, but with some special constructional provisions to ensure technically acceptable characteristics in the compacted soil [23]. It may be interesting to mention some of the experiments carried out in Tamanrasset (Algeria), Kenya, and Sudan during the 1970s in connection with the construction of the Trans-Saharan highway. There has been a renewed awareness of the socio-economic potential of low water compaction in these regions recently. However, this work has unfortunately not been continued to obtain the application of such a technique. The main goal of this study is to evaluate the feasibility of dry compaction experimentally, using novel combinations of some materials. Hence, using the combination of tuff and limestone materials to minimize the amount of water for the road construction compaction is investigated. Finally, different combinations of tuff and limestone sand were evaluated with the Proctor and California Bearing Ratio (CBR) tests, and their results were discussed.

2 Methods and Materials

2.1 Materials

The materials used in this study were obtained from Djebel Antar, which is located 44.4 km from Bechar (Algeria). The first material was tuff. This material is extracted from a quarry that is frequently used for road construction projects. The second material was limestone sand, which is a by-product of local quarries, that contains a high quantity of fines. It was characterized by a spread particle-size distribution, and its maximum diameter was about 5 mm, which was insensitive to water. Due to its good compatibility, it is ideal as a base course material for road construction projects. These materials are demonstrated in Fig. 1.

Fig. 1: a) Tuff; b) limestone sand materials before sieving.

2.2 Physical and Chemical Properties of Materials

The geotechnical and chemical identification tests were done to classify the materials and compare them with the specifications and standards adopted for their use in road structures. These tests are conducted at the West Public Works Laboratory based on well-specified standards. The tuff and limestone sand gradations are illustrated in Fig. 2. As can be seen, tuff had a spread particle size, according to the Laboratory of Public Works in Algeria [24].

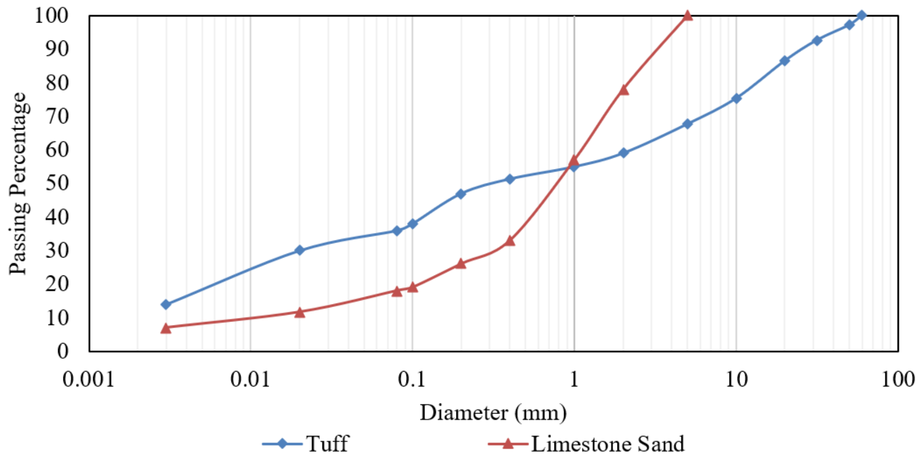

Fig. 2: Tuff and limestone sand gradation.

The physical and chemical properties of these materials are also summarized in Table 1. Atterberg limits test showed tuff's plasticity index was 9.2%. According to the limit values, it was concluded that this is a low-plastic material that has low swelling. The plasticity limit of the limestone sand could not be measured because the pellets fragmented before they reached a diameter of 3mm. The Los Angeles test was also conducted on this material to evaluate its abrasion resistance. The test result value was about 50%. Therefore, the extraction and implementation of this material were simple. The x-ray chemical analysis tests revealed that more than 55% of tuff is constituted by $CaCO_3$, and it is classified as a non-aggressive material of a carbonate nature with little silica. This test also indicated that limestone sand had 70% of $CaCO_3$.

Table 1: Physical and chemical properties of tuff and limestone sand.

Physical Properties	tuff	limestone sand	Chemical Properties (Minerals)	tuff [%]	limestone sand [%]
Plasticity index [%]	9.2	-	$CaCO_3$	55.1	70
Los Angeles [%]	50	-	NaCl	0.14	0.18
Density [g/cm^3]	1.9	2.6	Insoluble	0.14	38.12

2.3 Standard Proctor Test on Different Combinations of Tuff and Limestone

The effect of adding different percentages of limestone sand to the 100% tuff was evaluated. The main objective was to investigate the changes in physical characteristics of maximum dry density (γ_{dmax}) and optimum water content (ω_{opt}) as a function of tuff and limestone sand percentages. Thus, four different combinations, including 100 % tuff, 80% tuff + 20% limestone sand, 70% tuff + 30% limestone sand, and 60% tuff + 40% limestone sand were examined with the standard Proctor test. This test aims to find the optimum water content and the maximum dry density for standardized compaction of a certain intensity. This test was done according to the NF P 94-093 standard [22]. The Procedure is shown in Fig. 3.

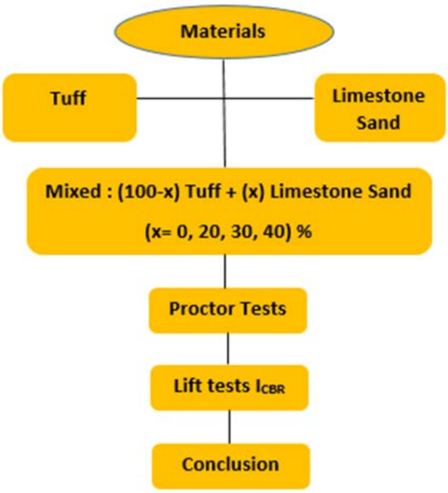

Fig. 3: The process of finding the best tuff-limestone combination.

2.3.1 Adding Lime Powder to the Main Mix

Considering the main mixture (60% tuff and 40% limestone sand) and its density, 1%, 2%, and 3% lime powders were added to this mixture. Indeed, the effect of adding different percentages of lime to the "tuff-limestone sand" mixture was examined. Likewise, the main objective was to find out the variation of the physical characteristics (γ_d, ω_{opt}) as a function of lime contents. The preparation of the mixtures (tuff-limestone sand, lime) was carried out in the same way as the compaction steps to evaluate the optimum water content and maximum dry density with the standard Proctor test. The procedure for this test is demonstrated in Fig. 4.

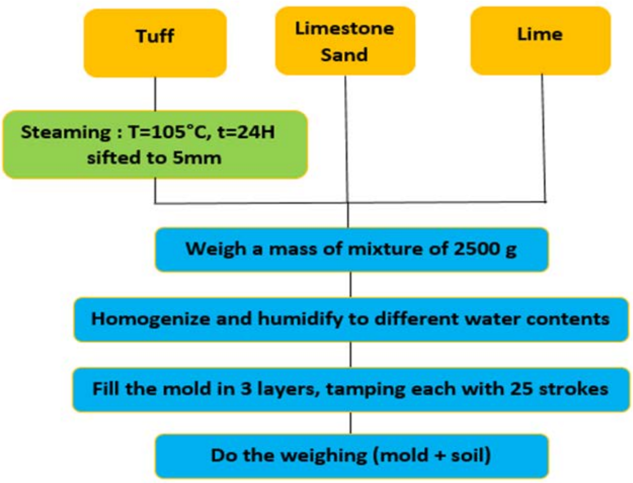

Fig. 4: The standard Proctor procedure for tuff-limestone and lime materials.

2.4 California Bearing Ratio (CBR) Test

The bearing capacity of the soil is its resistance to rupture determined by the California Bearing Ratio (CBR) based on the NF P 94-078 standard [22]. The CBR test measures the relative bearing capacity of soils in comparison with a standard reference soil. It allows for checking the behavior and densification resistance of materials to water. The CBR indexes were calculated based on the standard for different combinations of tuff, limestone sand, and lime materials. For instance, the CBR index (I_{CBR}) for 2.5 mm was calculated with Equations 1 and 2. I_{CBR} indicates the strength of the subgrade of a road, paved area, or railway track. It is determined based on the ratio of a metal piston penetration load to the standard load for that penetration.

$$I = \frac{F(2.5)}{F_S(2.5)} \times 100 \quad \textit{For Index bringing to 2.5mm.} \tag{1}$$

$$I = \frac{F(5)}{F_S(5)} \times 100 \quad \textit{For Index bringing to 5mm.} \tag{2}$$

Where:
I - the CBR index (I_{CBR}) at 2.5mm penetration,
F(2.5) - the amount of applied load at 2.5 mm penetration,
$F_s(2.5)$ - the standard load at 2.5 mm penetration. And the same with 5 mm.

3 Results and Discussion

3.1 Proctor Test Results

The experimental results for the characteristics of normal Proctor compaction are depicted in Table 2 and Fig. 5. Regarding Fig. 5, As can be seen, compared to the 100% tuff mixture, adding limestone sand improved the optimum compaction characteristics of the mixture. The limestone sand increased the maximum dry density from 1.967 to 1.996 and reduced the optimum content from 11.7 to 10.5, and it enhanced the compaction ability of the mixture. Hence, the mixture containing 60% tuff and 40% limestone was recommended for road construction, especially in areas with a water shortage.

Table 2: Proctor characteristics as a function of limestone sand content.

Mixtures	100 % tuff	80 % tuff + 20 % LS	70 % tuff + 30 % LS	60 % tuff + 40 % LS
Maximum dry density [g/cm^3]	1.967	1.940	1.923	1.996
Optimum ω_{opt} [%]	11.7	11.9	12.3	10.5

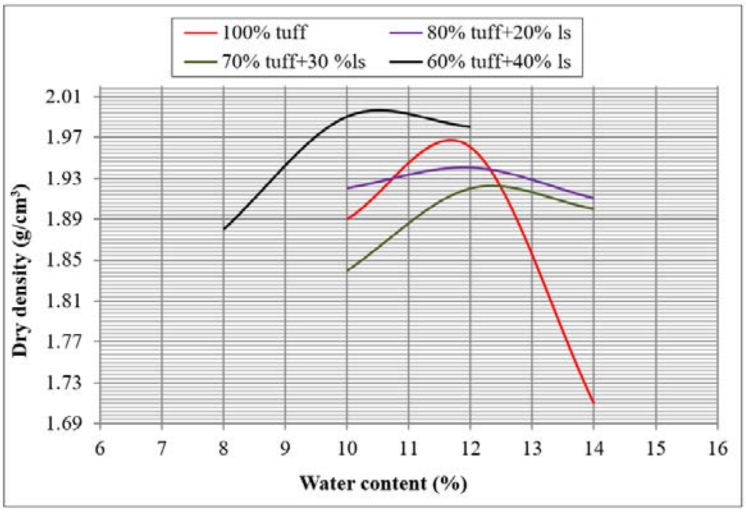

Fig. 5: Dry density and water content for test combinations.

3.2 California Bearing Ratio (CBR) Test Results

The CBR indexes of 100% tuff were calculated with Equation 1, and the results are reported in Table 3. Indeed, 2.5 mm and 5 mm penetration indexes were calculated, and the larger value was chosen as the CBR index, which was 10 for 100% tuff. The same method was applied for all mixtures, and the results of the CBR index of the different percentages of tuff and limestone are shown in Table 4. The correlations between load and penetration depth for these test combinations are also demonstrated in Fig. 6, using the correlation equations [25].

Table 3: The CBR values for 100% tuff.

Time [min]	Penetration [mm]	Reader	Total Load [KN]
1'	1.25	2	0.4347
1'40"	2	3	0.6521
2'	2.5	5	1.0869
4'	5	9	1.9565
6'	7.5	15	3.2608
8'	10	21	4.5652

Table 4: The CBR index values for different combinations.

Mixtures	80% tuff +20% LS	70% tuff +30% LS	60% tuff +40% LS
$I_{CBR\ [\%]}$	6	13	25

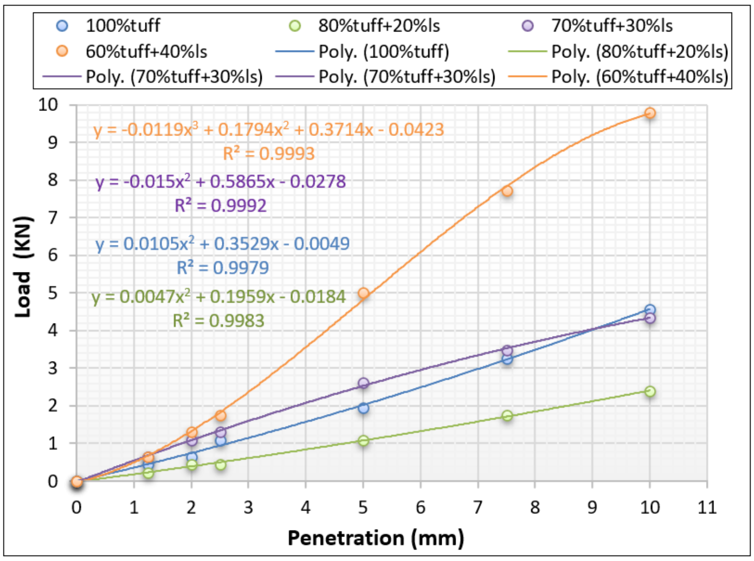

Fig. 6: The correlation between load and penetration for test combinations.

Considering this figure, the following important points can be highlighted:

- The curves obtained from immediate CBR tests at water contents indicate that the material shows better resistance when the water content decreases.
- The mixture of 60% tuff with 40% limestone sand showed a suitable resistance (I_{CBR} = 25).
- Regarding these polynomial equations for the different mixtures of the study, the correlation coefficient was very high (R^2 = 0.998), indicating the validity of the experimental results.

3.3 The Proctor Test Results of the Added Lime Mixes

The results of the normal Proctor compaction test are shown in Table 5 and Fig. 7. According to these results, the added lime had no significant effect on improving the physical characteristics of the chosen mixture (60% tuff+40% limestone sand). More importantly, using 1%, 2%, and 3% lime powder increased the optimum water content by 20%, 20%, and 40%, which was against the aim of this study for water conservation). Hence, it is not recommended to use it as an additive material.

Table 5: The Proctor Test Results for different lime contents.

Mixtures	Compaction Characteristics	
	Optimum water content ω_{opt}[%]	**Maximum dry density (g/cm^3)**
60 % tuff + 40 % LS [Main combination]	10.5	1.996
Main combination +1% lime	12.0	1.960
Main combination +2% lime	12.0	1.939
Main combination +3% lime	13.9	1.900

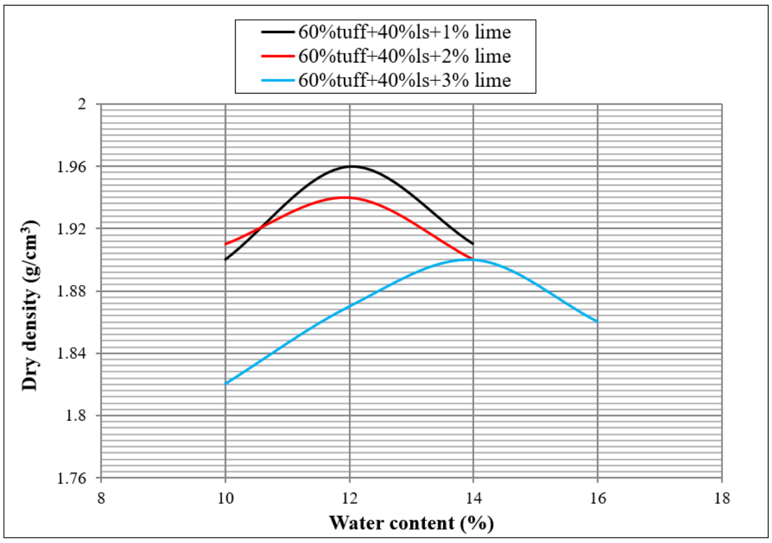

Fig. 7: Effect of lime on compaction characteristics.

3.4 The Proctor Test Results of the Added Lime Mixes

The CBR test results for the added lime mixtures are depicted in Table 6. Considering these results, it is noticeable that the values of the CBR index were raised by increasing the amount of lime for the optimum mixture, which simultaneously requires larger amounts of water to have this hardness, which is practically logical. The relationships between the applied load and penetration for these mixtures are also depicted in Fig. 8.

Table 6: Result of the CBR index.

Mixtures	60% tuff +40% LS	60% tuff +40% LS+1% Lime	60% tuff +40% LS+2% Lime	60% tuff +40% LS+3% Lime
I_{CBR}	25	12	16	38

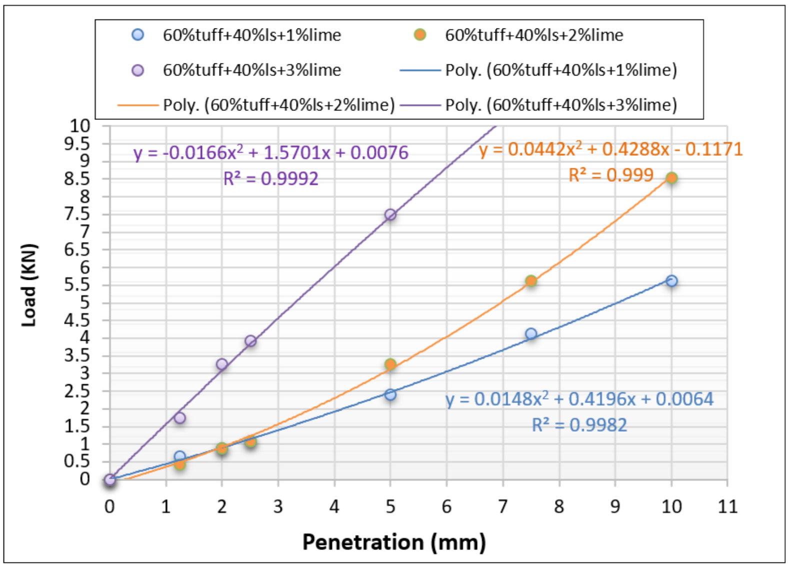

Fig. 8: The relationships between the load and penetration for different added lime mixtures.

Considering these results, the value of the CBR index increases depending on the quantity of lime added to the optimal mixture, and this also requires at the same time a significant quantity of water to have this hardness. The correlation coefficient of the polynomial equations for the different mixtures of this study was very high (R^2=0.999). This accuracy confirms the correlation of the experimental results.

4 Conclusion

This research was chosen because of the problems caused by the shortage of water resources in arid or desert regions to make better use of the materials near the road construction site. Considering the road construction in arid regions, the major difficulty of these projects stems from the lack of water. Indeed, the objective of this study is the improvement of soil compaction by using tuff and limestone sand (waste of a quarry) at minimum water content. Hence, standard Proctor and CBR tests on the mixture containing different percentages of tuff and limestone sand revealed that the water content decreases and the maximum density increases after adding limestone sand to the 100% tuff mixture. Moreover, the CBR index demonstrated that the best tuff-limestone sand combination should contain 60% tuff and 40% limestone sand. Besides, three different percentages of lime were added to this optimum mixture and, Proctor and CBR tests showed that lime had no significant impact on improving the mechanical properties of this mixture, and it can increase the required water for compaction which is not desirable in arid areas. It is vital in arid regions to minimize the amount of water as much as possible. Therefore, using limestone sand and tuff combination for the compaction of road construction can be a suitable solution. Applying this method in real road construction projects has both economic and environmental benefits which can preserve the underground water and reduce the road construction costs. In the studied region, limestone crust tuffs are available in large quantities. Whereas, this scientific technique has a very important role from the point of view of valorizing local materials, to minimize the cost of the project and ensure good sustainable development for the base layers. Besides, the strength of the base course and subbase course layers containing tuff and limestone sand can be evaluated with some cost-effective methods, such as Humboldt Geogauge and Clegg impact soil tester machines [26].

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