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A Novel Wildfire Residue for Stabilization of Laterite Soil

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Abstract The annualized economic burden to United States in 2016 from wildfire is estimated to be between $71.1 billion and $347.8 billion. The cost of wildfire to Indian economy is at least USD148 million (₹1,100 Crores). One of the plants with high associated risk to wildfire is Calotropis Procera (CP). Thus, there is a great opportunity to explore materials which upkeep the good health of forest eco system, stabilize soil slopes in forest areas and serve as an alternative material for construction. Current research focuses towards application of various industrial wastes. There is a lot of scope for exploring the potential of re-using the residue collected from wildfires in the areas surrounding forest. There is an adequate scope to raise an alternative material to cement to reduce carbon emissions and achieve sustainability of resources used in the manufacture of cement. India has 10.6% of the hill-slopes covered with laterite soils which are prone to frequent slope failures. In the present study, an innovative combination of materials "1) Ash of Calotropis Procera plant (Highly inflammable) – ACP (Derived from forest fires) and 2) Metakaolin – MET (An alternative cementitious material) were utilised to stabilize lateritic soil-LS. Proctor heavy compaction test was conducted to study the minimum water content required to achieve the highest value of unit weight of the resulting combinations. Various proportions of ACP used were "2%, 4%, 6%, 8% & 10%". Various proportions of MET used were "0.2%, 0.4%, 0.6%, 0.8% & 1.0%". Out of five combinations of Laterite soil(LS), Ash produced by burning Calotropis Procera (ACP), and Metakaolin (MET), the combination-3 i.e., LS+ 6% ACP + 0.6% MET gave rise to the highest value of unit weight in heavy compaction. The optimum moisture content achieved is 12% and the highest value of unit weight achieved is 20.8 kN/m^3.

Keywords Ash of Calotropis Procera, Metakaolin, Lateritic Soil, Proctor Heavy Compaction, Minimum Water Content, Highest Value of the Unit Weight

1. Introduction

"I'd rather fight 100 structural fires than a wildfire. With a structural fire you know where your flames are, but in the woods, it can move anywhere; it can come right up behind you"- Tom Watson. The annualized economic burden to United States in 2016 from forest fire (Wildfire) is estimated to be between $71.1 billion to $347.8 billion [22]. Forest cover in India is 7, 64, 566 square kilometers. India State of Forest Report (ISFR) 2015 mentions that approximate fire prone areas as 2.40 per cent, 7.49 per cent and 54.40 per cent under heavy, moderate, and mild fires respectively. The area vulnerable to wildfire is 64.29% out of the total area covered under forests. In India half (383 districts) of total number of districts (766 in 2022) suffer from wildfire [23]. The cost of wildfires to Indian economy is at least USD148 million (₹ 1,100 Crores INR). Wildfires are classified into four groups. They are "Surface fires, Underground fires, Ground fires, Crown fires". The most frequent forest fire occurs due to surface fire. Litter, debris, and small plant shrubs contribute to fire in surface fire category. This fire not only burns ground flora but also engulfs the undergrowth and the middle story of the forest

[24]. One of the plants with a high associated risk of wildfire is Calotropis Procera (CP).

Another problem associated with construction in tropical or subtropical forest areas is the failure of laterite soil slopes.

Yet, another problem worth noting is emission of CO_2 due to the production of Cement. Cement manufacture produces about 8% of the world's carbon dioxide (CO_2) emissions [26].

Thus, there is a great opportunity to explore materials which upkeep the good health forest ecosystem, stabilize soil slopes in forest areas and serve as an alternative material for construction.

2. Literature Review

Ashes derived from Butyrospermum Parkii (Shea tree, hardwood) and Eriodendron Orientale Kostel (white silk tree, softwood) trees were added to study the impact on improving penetration resistance of soil. The test results showed an increase in consistency limits. An improvement in penetration resistance also was measured through CBR test [1]. The possibility of stabilizing Marl soil with volcanic ashes (Natural pozzolans) was studied. A decrease in the cost of construction, time of building, and increase the strength were reported [2]. Cement (C) and Rice Husk Ash (Ash derived from burning of rice, RHA) were used for stabilization of residual soil. The experimental results showed a reduction in plasticity of the soil, decrease in the maximum dry unit weight, and increase in the corresponding optimum moisture content. The highest value of the maximum dry unit weight and moisture content produced due to the addition of cement (6–8%) and rice husk ash (10–15%) to the residual soil [3]. Potential of Bagasse ash (Ash produced by burning sugar cane pulp and a byproduct of sugar Industry) as a pozzolanic material was investigated as a novel sustainable material for stabilisation of expansive soils. Bagasse ash, lime combination enhanced shear strength of swelling soil by 815%, bearing capacity by 9.2 times and compressibility by 83% due to high amorphous silica properties of Bagasse ash [4]. Experimental studies were carried out by mixing ash derived from cow dung and husk to the soil. Results of the laboratory tests showed a multifold improvement (15 times) in penetration resistance of soil [5]. Experimental results showed that cement as an additive is superior to lime. Combination of cement and "Waste From Sludge (WFS)" exhibited excellent California Bearing Ratio values [6]. Two varieties of Biochar (Burnt sewage treatment sludge) activated blast furnace slag mixes were used to assess alternative cementitious to cement. The biochar to slag ratio of "0.67:0.33" was observed to produce a strength of about 1243 kPa [7]. Yet, in another experimental investigation, phosphogypsum was blended with cement and fly ash to stabilize the loess. Treatment with cement (10%) and phosphogypsum generally reduced the plasticity index. Compressive strength of the order of 18.64MPa was obtained [8]. Experimental investigation was made to understand suitability of waste residue obtained from foundry industry i.e., Sand sized "Byproduct" as subbase material or as a fill material. For imparting cohesion, sand is mixed with cement and lime (2%, 4%, 8% and 10% by weight). Comparative study was made with the addition of cement and lime [9]. Experimental investigations were carried out with bagasse ash and calcium carbide residue. Gain of shear strength of soil was directly proportional to amount of bagasse ash. Presence of organic matter reduced shear strength and maximum dry density of expansive soil [10]. In another experimental investigation, combination of Rice Husk Ash (RHA) and lime were used (20%, 2%). Penetration resistance of expansive clay was improved by administering the above combination by 800% while plasticity was reduced by 90%, and free swell was reduced by 70% [11]. The properties of two coal ashes viz., Bituminous (Class F) and subbituminous (Class C) were compared with respect to their cementitious properties. Class F fly ash does not produce self-cementing properties, while Class C fly ash exhibits the same. Class F fly ash will be cementitious with the addition of activators like lime. Class C Fly ash was a viable low cost raw material for stabilization of soil in a wide variety of construction applications [12]. The effect of ash derived from palm oil fuel and peat was studied. The test results have shown a multifold improvement in dry unit weight (4 times) and California bearing ratio (31 to 42 times) of road sub-base [13]. Experimental investigations were carried out on swelling soils (Rich in sulfates). Bituminous fly ashes, sub-bituminous fly ash, and synthetic fibers (polypropylene and nylon) were utilized as potential stabilizers to study soil swell. Bituminous fly ash mixed with nylon fibers was observed to be the best combination to inhibit soil swell [14].

Another study focused on application of various types of fly ashes (Self cementing and without activators) for the stabilizing four varieties of soft subgrades for pavements. The strength approaches were applied to estimate the optimum mixture design and to determine the thickness of the stabilised subsoil layer. Achievement of strength in compaction depends mainly upon amount of ash, moisture content used and nature of compaction. Continuous curing time of 7 days was required to obtain best results while performing either unconfined compression test or California bearing ratio test. Compaction of the soil was delayed by 2 hours to simulate delays that are inevitable in field construction practices [15]. An innovative method of representing the compaction data was presented. Compaction of Fly ash simulates compaction of cohesionless soil [16]. Groundnut shell ash (Agricultural waste) and cement were used for stabilizing the highly compressible soil. The experimental results showed a note

-worthy improvement in strength and durability parameters [17].

2.1. Summary of the Previous Work

Nowadays, researchers focus on application of by-products from several industries e.g., Aluminum, Cement, Ceramic, Copper, Fertilizer, Forging, Glass, Mining, Rice, Sugar, Steel, and Thermal power plants. There is much scope for 1) "Exploring the potential of re-using the residue collected from wildfires in the fringe areas surrounding forest" and 2) "Raising an alternative cementitious material e.g. Metakaolin for stabilizing hill slopes". It is apparent that this strategy leads to low carbon as well as sustainability.

3. Materials and Methods

In this section materials were introduced and their typical properties are presented.

3.1. Materials Employed in this Research

The following materials were used and a brief discussion is mentioned below.

3.1.1. Laterite Soil (LS)

Laterite soil is a derivative of weathering from varied rock types under intense oxidizing as well as leaching environments. It forms in humid climates s (Prevalent in tropical as well as subtropical regions). Laterite soil varies in color from reddish to yellow. Lateritic soils contain minerals of clay (In some cases weathering conditions will not be adequate to form clay minerals) but they do not contain silica mineral. Laterite soil is rich in iron oxide. Laterite soils contain minerals of hematite, titanium oxides, aluminum oxides and aluminum hydroxides (Goethite, $HFeO_2$; FeO (OH); and hematite, Fe_2O_3; gibbsite, $Al_2O_3 \cdot 3H_2O$ and bauxite). In India, laterite soil is widespread covering over 10.6% of the total geographical area. It is present on the slopes of Eastern Ghats (Andhra Pradesh, Assam, Jharkhand, Meghalaya, Odisha, and West Bengal), Western Ghats(Gujarat, Karnataka, Kerala, southern and western Maharashtra). The problem with the lateritic soil is that it can be easily cut with a spade when moist, but it turns out to be as hard as iron when exposed to air. All hill slopes as mentioned above, stand tall and stiff in summer season but in monsoon period they are most prone to slope failure [25].

3.1.2. Calitropis Procera Plant Ash (CPA)

Calotropis Procera is a plant within the family of "Apocynaceae" that is found in Africa (North and tropical parts), Asia (South and western parts), Cambodia, Laos, and Vietnam [27]. Stems of the Calitropis plant were collected from Priyagraharam village (Latitude and Longitude: 18.4234° N, 84.1416° E), Srikakulam district, Andhra Pradesh, India, is shown in Fig. 1. Growth of calitropis plant near trees is as shown Fig. 2. It catches fire at 37^o centigrade(C) and it completely degrades at 290^o C. Burning 6 kilograms of Calotropis procera leaves an Ash(Residue) of 200g. It is such an inflammable plant upon drying. The residue (Ash) after burning Calotropis procera plant (ACP) is shown in Fig. 3.

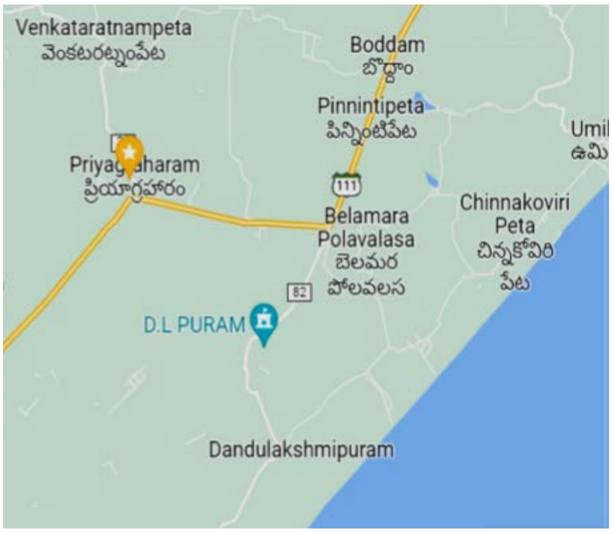

Figure 1. Location of Priyagraharam

Figure 2. CP Plant

Figure 3. ACP

3.1.3. Metakaolin

Metakaolin is a product of dehydroxylation of the mineral kaolinite through roasting (Not burning). Metakaolin thus produced is amorphous and pozzolonic (Highly). The deposits of kaolin are met within a number of states. Gujarat holds 41%, Karnataka holds 6%, Kerala holds approximately 23%, Odisha holds 6%, Rajasthan holds 16%,West Bengal holds 3% , and Andhra Pradesh, Jharkhand and Madhya Pradesh together hold 8% [28]. For experimentation purpose metakaolin is purchased from a local trader.

3.1.4. Water

Normal tap water available in the laboratory was used.

3.2. Method of Testing

Liquid and plastic limits of laterite soil (LS), ash(Wildfire residue) of Calitropis Procera plant (ACP) and Metakaolin (MET) were determined [18]. Grain size analysis of LS, ACP and MET was conducted [19] and the fractions of various particles are determined.

Heavy compaction test [21] was performed on i) Pure laterite soil (LS), ii) Laterite soil was blended with ACP in some proportions (hereinafter called "LSACP"). Best combination of laterite soil and ACP was identified.

In another set of experiments, laterite soil (LS) was blended with metakaolin (MET) in some proportions (hereinafter called "LSMET"). Best combination of laterite soil and metakaolin was identified.

In yet another set of experiments, LS was blended with the best proportion of ACP and some other proportions of MET (hereinafter is called as "LSACPMET").

The best combination of LS, ACP(best proportion as determined through above set of experiments) and MET(best proportion as determined through above set of experiments) to yield LSACPMET which in turn has shown the highest Unit weight, Optimum Moisture content. The various combinations were tested as listed in Table 1.

3.2.1. Heavy Compaction Test

Indian version of the Modified Proctor Test, known as "Heavy compaction test", was conducted as per IS-2720 Part 8:1983(Reaffirmed- May 2015) [21]. This test was done to simulate heavily laden traffic conditions.

A 5-kilogram sun dried soil sample passing through the 19mm Indian Standard test sieve was used. The soil sample was mixed thoroughly, sufficiently and carefully with 2% water. The soil types "LSMET" and "LSACPMET" were stored in a sealed container for 16 hours prior to the commencement of compaction test for allowing uniform distribution of water. The mold used was of 1000 cm^3 capacity. Mold along with its base plate were weighed to the nearest 1 g along with the baseplate. The mold was placed on a concrete floor. The extension collar was attached to the mold and it was filled with moist soil. The soil was placed in the mold + collar assembly in five equal layers (Approximately equal mass). It was made sure that the quantity of soil sample utilised was adequate to fill the mold, when the extension collar was removed. The soil thus placed was compacted. Each layer was delivered 25 blows with the help of 4.9-kg rammer. The rammer was made to drop from a height of 450 mm above the top most soil layer. It was ensured that the blows were distributed uniformly over the surface of each layer. The extension collar was removed and the compacted soil was leveled off cautiously to the top edge of the mold with the help of the metallic straightedge. The mold and soil were weighed accurately to the nearest to 1 g. The compacted soil was removed from the mold and was placed on the mixing tray. A representative soil from the above operation was collected and its water content was determined. The remaining soil specimen was broken up, scrubbed through the 19-mm Indian Standard test sieve and then mixed with the remainder of the original sample. The above procedure was repeated with additional increments of water (1% to 2%). The six cycles of the above procedure were repeated for each combination of "LSACP", "LSMET" and "LSACPMET". The highest values of unit weight and moisture contents were recorded.

Table 1. Various combinations of Laterite soil(LS), ash of Calotropis procera(ACP) and Metakaolin(MET)

Various combinations of LS and ACP (Combination of Laterite Soil and Ash derived from burning of Calotropis procera)	LS+2% ACP	LS+4% ACP	LS+6% ACP	LS+8% ACP	LS+10% ACP
Various combinations of LS and MET (Combination of Laterite Soil and Metakaolin)	LS+0.1%MET	LS+0.2% MET	LS+0.3% MET	LS+0.4% MET	LS+0.5% MET
Various combinations of LS, ACP and MET (Combination of Laterite Soil, Ash derived from burning of Calotropis procera and Metakaolin)	LS+6%ACP +0.2%MET	LS+ 6%ACP +0.4%MET	LS+ 6%ACP +0.6%MET	LS+ 6%ACP +0.8%MET	LS+ 6%ACP +1%MET

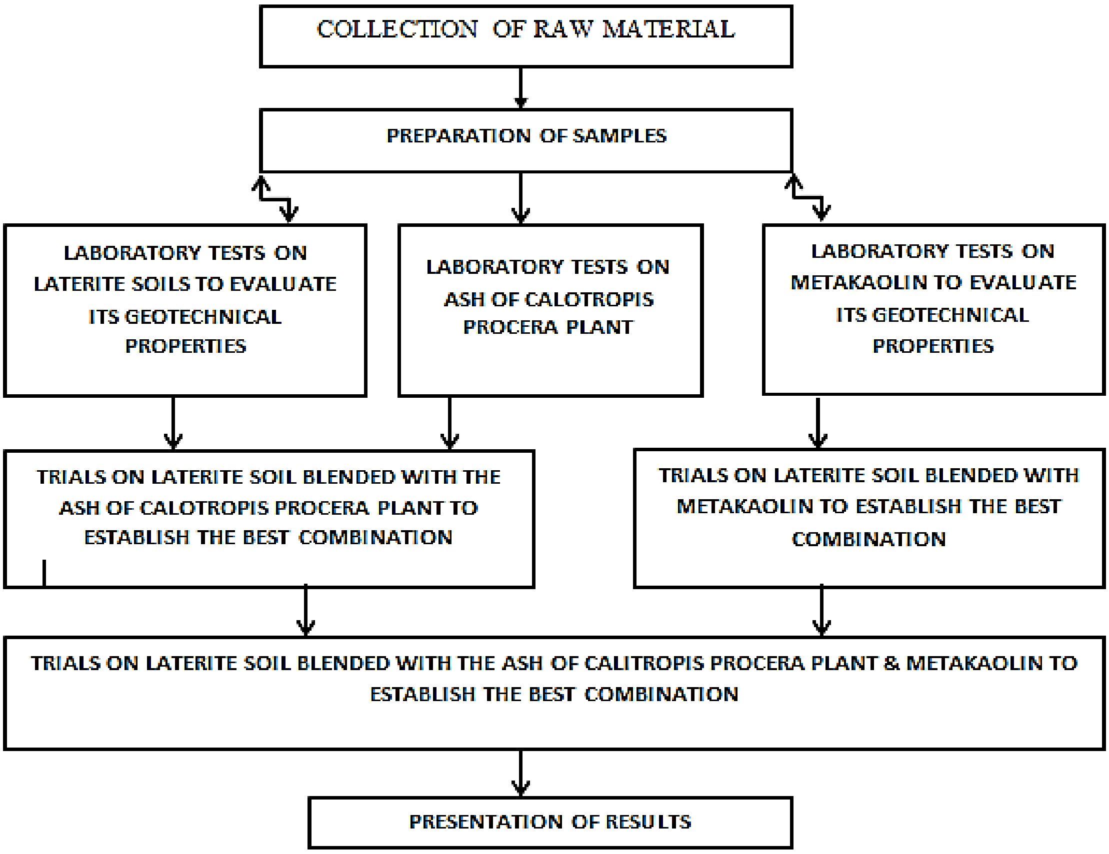

Figure 4. Scheme adopted for conducting experiments

After each cycle of compaction, extension collar was detached from the mold. The weight of the mold with the compacted soil was determined (Accurate to the nearest 1 gram). The weight recorded at this stage was W_2. The difference of W_1 and W_2 gave the weight of wet soil.

Bulk Unit weight was determined as a ratio of weight of wet soil upon volume of wet soil. Dry weight was determined. Dry unit weight was obtained from relevant formula. A graph was plotted between moisture content (MC) and Dry Unit Weight (UW). Method of Testing is depicted below in Fig. 4.

4. Results and Discussion

In this section the results and discussions are presented.

4.1. Consistency Indices

ACP is found to be non-plastic. Liquid limit and plastic limit of Laterite soil are found to be 33% and 12%. Liquid and plastic limits of metakaolin are found to be 29% and 19%.

4.2. Grain Size Distribution

Grain size analysis was performed on ACP and LS. The proportions of different soil particles were determined. In the ACP the coarse grained soil fraction (Sand) and fine grained soil fraction (Silt and clay fraction) were found out as 94%, 6% [19]. In LS the coarse grained soil fraction (Sand) and fine grained soil fraction (Silt and clay fraction) were found out as 76.5%, 23.5% [19]. The results of Grain size analysis conducted on ACP and LS are shown in Fig. 5 and Fig. 6.

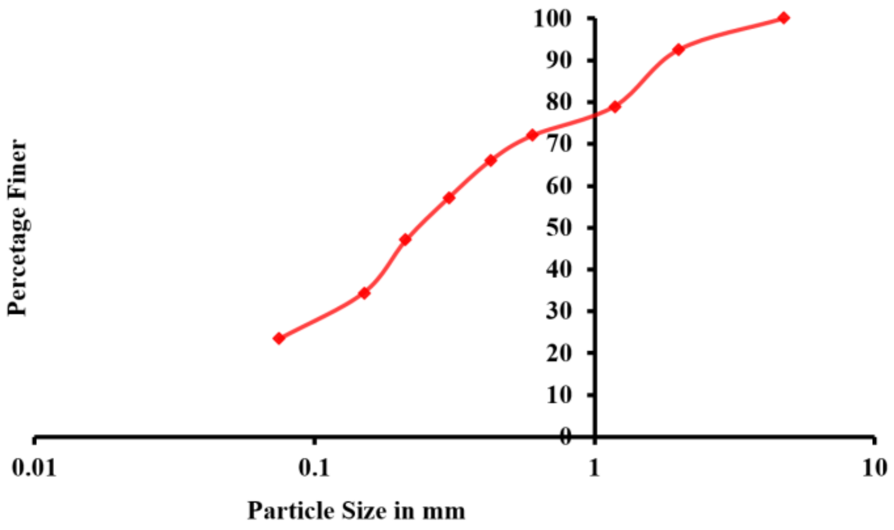

Figure 5. Grain Size Analysis – LS

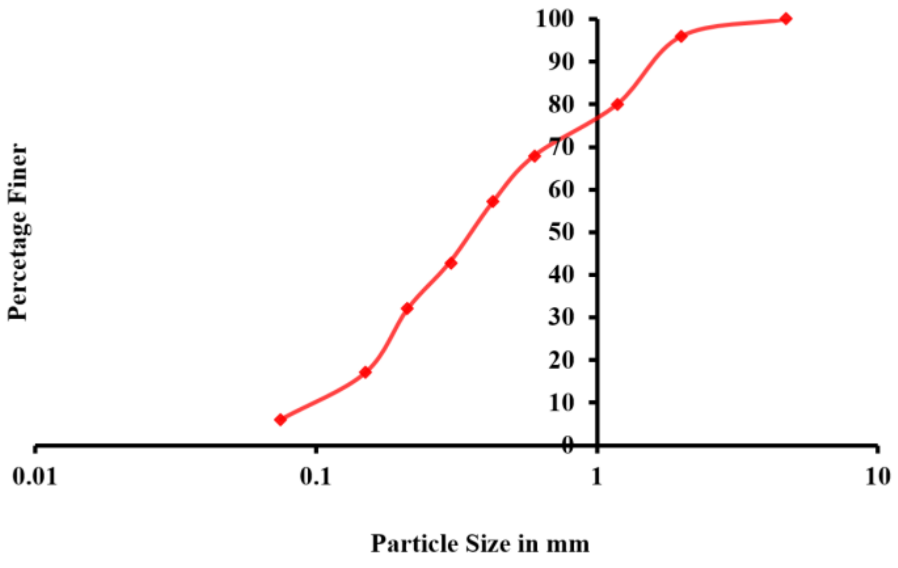

Figure 6. Grain Size Analysis – ACP

4.3. Soil Classification

Laterite soil is identified as poorly graded silty sand with group symbol SP-SC. Metakaolin is identified as inorganic silt of medium compressibility with group symbol ML [20]. The burnt ash was observed to be non-plastic.

4.4. Compaction

An experimental investigation to achieve "Heavy compaction" is accomplished by conducting modified Proctor test [21] on planned combinations of ACP, MET and LS.

Variation of Moisture Content (MC) *versus* Unit Weight (UW) for various combinations of ACP and LS are presented in Fig. 7, Fig. 8, and Fig. 9. During the performance of the modified proctor tests, the highest value of the maximum dry unit weight achieved by each combination was measured.

In the first set, various proportions of ACP (2%, 4%, 6%, 8% and 10%) were added to the LS and modified Proctor test was conducted. The highest value of unit weight achieved was 21.6kN/m^3 and Optimum Moisture Content (OMC) 13.4% for LS and ACP (6%) combination Fig. 7.

In the second set, with various proportions of MET (0.1%, 0.2%, 0.3%, 0. 4%, 0.5% and 0.6%) were added to the LS and modified Proctor test was conducted. The highest value of unit weight achieved was 21.5kN/m^3 and OMC 10.8% for LS and MET (0.5%) combination Fig. 8.

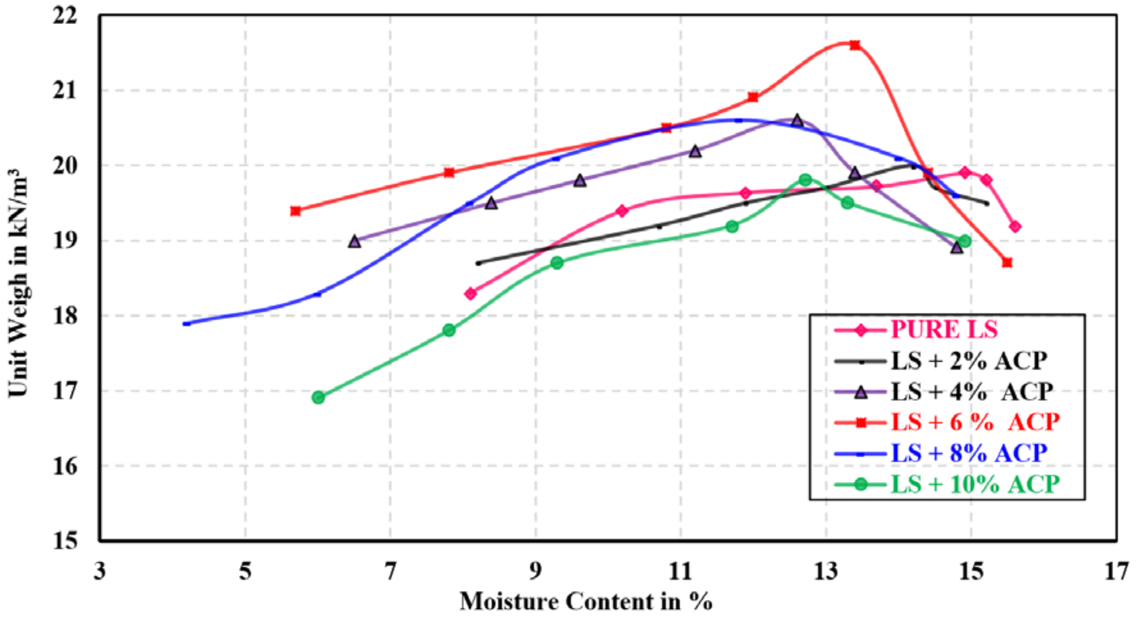

Figure 7. Variation of MC *versus* UW for various combinations of ACP and LS

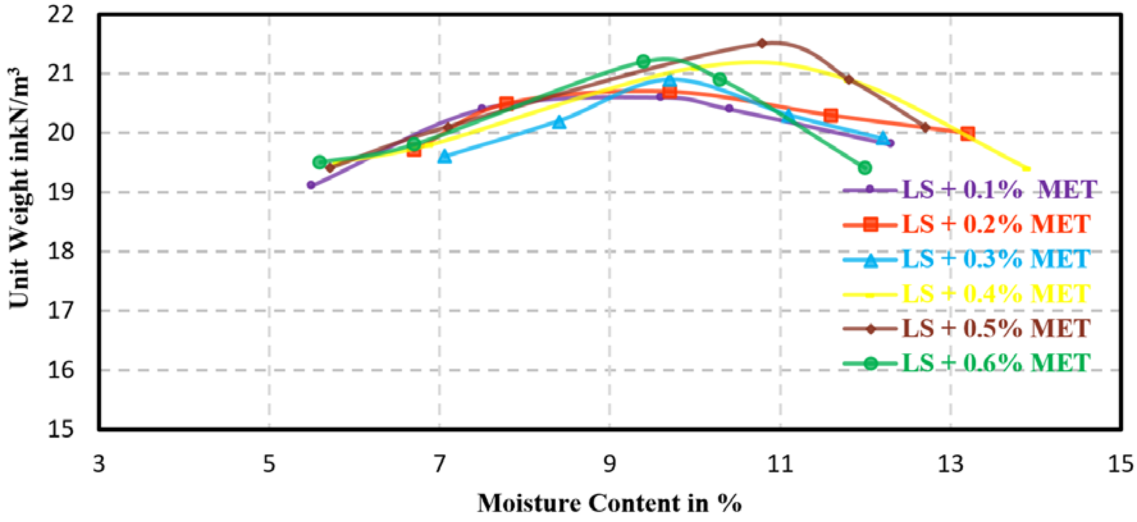

Figure 8. Variation of MC *versus* UW for various combinations of LS and MET

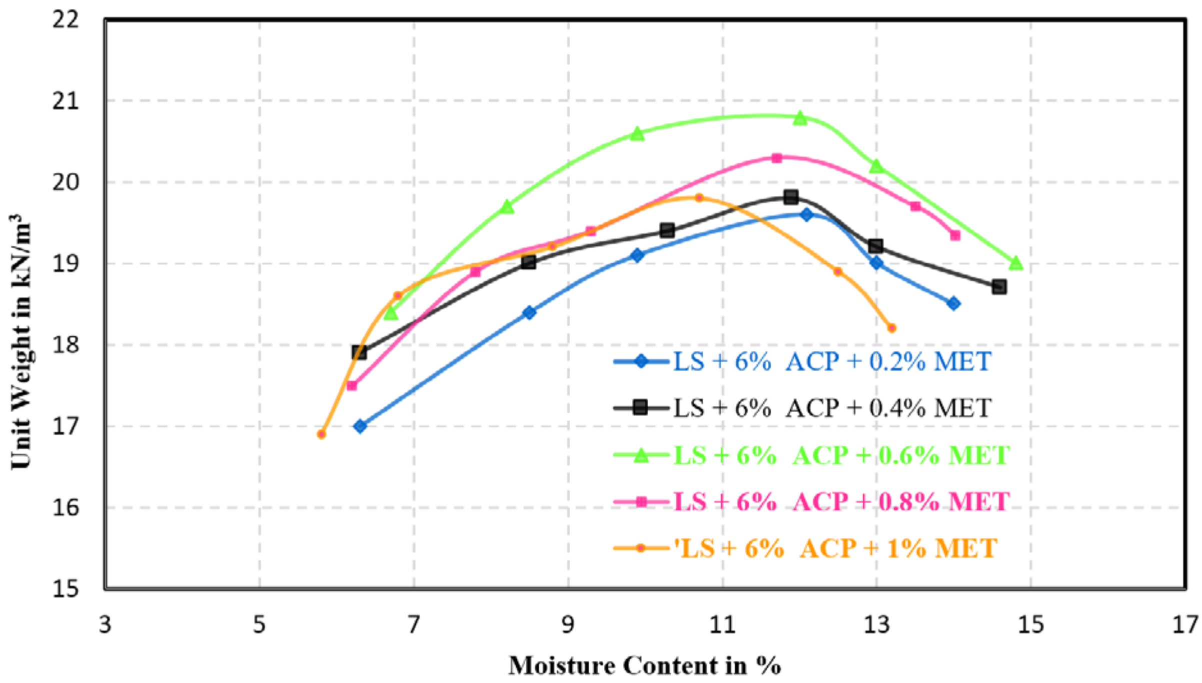

Figure 9. Variation of MC *versus* UW for various combinations of ACP, LS and MET

In the third set, LS was mixed with ACP (6%) and with various proportions of MET (0.2%, 0.4%, 0.6%, 0. 8%, 1.0%) were added to the LS and modified Proctor test is conducted. The highest value of unit weight achieved is 20.8kN/m^3 and 12% OMC for LS, ACP (6%) and MET (0.6%) combination Fig. 9.

Finally, due to addition of ACP and MET to LS unit weight increased by 4.3 % and OMC reduced by 24%. This effect can be understood due to prevalence of pozzolanic influence offered by MET.

4.5. Limitations of this Investigative Work

Converting Calotropis procera into ash and calcination of kaolin during the production of metakaolin require some carbon emission which may perhaps not be avoided.

4.6. Scope for Future Research

In India, one out of four people are reliant on produces from forests for their livelihood. Forest fires give rise to huge amounts of ashes. Ash produced by controlled burning of Calotropis procera has a great scope for stabilizing soil slopes/subgrade meant for pavements. It serves as a deterrent to wild.

5. Conclusions

Out of five combinations “Ash produced by burning Calotropis Procera (ACP), Laterite soil (LS) and Metakaolin (MET)”, combination-3 i.e ACP (6%) + LS+ MET (0.6%) gave rise to the highest value of the maximum dry unit weight in heavy compaction. The optimum moisture content achieved is 12% and the highest value of unit weight achieved is 20.8 kN/m^3.

ACP is an innovative construction material and there is a value addition to the residue of forest fires. Planned burning of Calotropis Procera plant (Inflammable soft wood variety) in the month of March every year prevents catching-up of fire in dry hot summer seasons in India (May be other parts of world also) near its villages, urban settlements, and areas in close vicinity of forests. Thus, it will be a first and foremost step in the deterrence of wildfires.

Use of metakaolin impedes the consumption of cement and at the same time indirectly prevents discharge of greenhouse gases produced during the burning of cement clinkers. Furthermore, it conserves additional resources necessary for the manufacture of cement. Thus, there is a great potential to achieve the sustainability of ecosystem.

Stabilization of Laterite soil prevents soil slope failure in forest setting or elsewhere.

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