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ORIGINAL PAPER

Sub-grade characteristics of soil stabilized with agricultural waste, constructional waste, and lime

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Abstract
The waste generated from the agriculture and construction sector is a serious threat to the environment due to its disposal problems. This study is an attempt to utilize agriculture and construction waste to stabilize the geotechnical properties of clayey soil to use the composite as sub-grade material. For this purpose, rice husk ash (agriculture waste) and construction demolition waste (used construction waste) are mixed in varying amounts in clayey soil alone and along with lime to obtain the best sub-grade material. The results of the experimental testing reveal that the geotechnical properties of clayey soil are improved by stabilizing it with various waste materials thereby solving their disposal problem thus sustaining a healthy environment. The use of wastes and lime in combination improves the unconfined compressive strength, California bearing ratio, and resilient modulus of the composite. The mix obtained on the addition of rice husk ash and construction demolition waste along with lime can be used as a sub-grade material thus achieving higher economic benefits.

Keywords Rice husk ash · Construction demolition waste · UCS · CBR · Resilient modulus · Pavement thickness

Introduction

Clayey soils, often deposited in semi-arid and arid regions all over the world, exhibit dual behavior of swelling and shrinkage, as these are susceptible to undergo large volumetric changes due to varying water content. Due to this behavior, these soils pose serious construction problems resulting in differential settlements to the structures resting over them. Due to the rapid growth in the infrastructure sector and limited availability of good soil (possessing adequate bearing capacity), the engineers are forced to build foundations over clayey soils possessing low bearing capacity. The stabilization of these soils using some pozzolanic materials and/or chemicals is adopted to improve their strength characteristics.

The waste generated from different sources is a major concern to the environment due to its disposal problem. India's economy primarily depends upon agriculture, and rice is a major grown crop in India contributing to more than 40% of the country's total food production. During the processing of rice from paddy in rice mills, a lot of rice husk is generated which is a cellulose-based fiber containing around 20% silica. This rice husk is burnt and around 1/5–1/4 is changed into ash. The ash produced on the burning of rice husk is known as rice husk ash and is successfully used as an additive in refractory bricks, cement, etc. Some past researchers have used rice husk ash in soil stabilization (Basha et al. 2005; Choobbasti et al. 2010; Ashango and Patra 2016; Karatai et al. 2017; Rahgozar et al. 2018; Liu et al. 2019). The bentonite soil was stabilized using rice husk ash and cement and observed that plasticity and compaction characteristics improved by adding 15% RHA and 6% cement content (Basha et al. 2005). The addition of RHA and lime in the optimum amount in clayey soil improved liquid limit, optimum moisture content, CBR value, and strength characteristics and decreased maximum dry density and deformability (Choobbasti et al. 2010; Rahgozar et al. 2018). The stabilization of clayey soil by using steel slag, lime, and rice husk ash revealed an increase of about 58–78% in stiffness thus making the suitability of the mix to be used for sub-grade of pavement (Ashango and Patra 2016). A

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combination of 20% rice husk ash and 2% natural lime increased the CBR value of expansive clay to about 800% (Karatai et al. 2017). The addition of rice husk ash and calcium carbide residue reduced curing time, swelling potential, crack quantity, and swell pressure and increased the unconfined compressive strength of clayey soil (Liu et al. 2019).

The rapid growth in the infrastructure sector has led to the generation of a large amount of construction waste all over the world. This waste is dumped in a barren land or along the roads thus leading to environmental degradation. Due to the pozzolanic behavior of construction demolition waste, it is successively used in improving the strength of concrete to solve its disposing problems. The use of construction demolition waste in improving soil characteristics is limited to date as few researchers have carried out research on using construction demolition waste in soil stabilization (Fatta et al. 2003; da Conceição et al. 2011; Arulrajah et al. 2013; Sharma and Hymavathi 2016; Sharma and Sharma 2019). The construction demolition waste can be successfully applied in pavement design, concrete technology, and soil stabilization thus solving its disposal problem (Fatta et al. 2003). The triaxial testing carried out on construction demolition waste stabilized soil revealed that the mix obtained can be used in the construction of pavements (Fatta et al. 2003; Sharma and Sharma 2019). The soil stabilized using construction demolition waste can be successfully used for the design of the sub-base course of low volume traffic roads due to its increased CBR value (da Conceição et al. 2011; Arulrajah et al. 2013; Sharma and Hymavathi 2016; Sharma and Sharma 2020).

The use of lime in soil stabilization is a common practice to improve its geotechnical characteristics. A lot of researchers have used lime in improving the sub-grade and strength characteristics of clayey soil (Bell 1996; Hossain et al. 2007a, b; Kavak and Akyarli 2007; Harichane et al. 2011; Dash and Hussain 2012; Panjaitan 2014; Asgari et al. 2015; Sharma and Hymavathi 2016; Pereira et al. 2018; Bhardwaj and Sharma 2020). The addition of lime to clayey soil increased OMC and CBR and decreased MDD and plasticity (Bell 1996; Kavak and Akyarli 2007). The utilization of locally available soil along with volcanic ash lime to stabilize soil proved to be cost-effective (Hossain et al. 2007a, b). The soft soil stabilized using lime and natural pozzolana reduced the construction cost and proved to be economical (Harichane et al. 2011). The addition of lime to clay initially increased the plasticity index up to 3% content and then further addition of lime decreased the overall plasticity index. Furthermore, there was a decrease in maximum dry density and the increase in OMC and UCS value on adding lime to clayey soil (Dash and Hussain 2012; Asgari et al. 2015). On adding construction demolition waste, fly ash, and lime together, there was a decrease in the differential free swell and maximum dry density and an increase in OMC, UCS, and CBR values (Panjaitan 2014; Sharma and Hymavathi 2016). The addition of lime to clayey soil improved the mechanical strength and load-carrying capacity of the overall composite (Pereira et al. 2018). The addition of lime, waste foundry sand, and molasses alone and together in expansive soil decreased the plasticity index and maximum dry density and increased OMC and UCS value (Bhardwaj and Sharma 2020).

Based on the literature review, the present study focuses on the utilization of rice husk and construction demolition waste alone and along with lime to improve the geotechnical characteristics of clayey soil to use it as sub-grade material. The bulk utilization of these wastes in the construction of sustainable and economical roads can reduce the requirement of conventional construction materials, misuse of land for haphazard dumping, and cost of road construction besides saving the environment from adverse effects of wastes.

Materials

Soil

The soil (Fig. 1) used in the study is obtained from the side of a link road that joins NH 103 nearby Hamirpur city, Himachal Pradesh, India. The soil was sealed in air-tight bags after oven drying it in the laboratory to avoid entry of any moisture. The gradation curve of soil obtained using wet sieve analysis and hydrometer analysis shows that soil is clayey as around 25% of the particles possess size less than 2.0 μm (Fig. 2). The geotechnical properties of soil reveal that it is highly plastic having an activity value of 1.30 showing the presence of montmorillonite mineral. The various geotechnical and chemical characteristics of clayey soil are tabulated in Tables 1 and 2 respectively.

Rice husk ash

The rice husk is procured from Raja rice mill industry, Ludhiana, Punjab, India, since Punjab is amongst the top 5 states in producing rice accounting for around 10% of the total production of rice in India. The rice husk was burnt in a furnace in the mill under a controlled temperature of around 500–600 °C for a period of around 1 h to keep silica in an amorphous state and to obtain rice husk ash (Fig. 2). The rice husk ash was tightly sealed in air-tight bags and was brought to the geotechnical engineering laboratory, NIT Hamirpur, to evaluate its geotechnical properties. The gradation curve of rice husk ash reveals that most of the particles possess a size below 75 μm (Fig. 2). The various geotechnical and chemical properties (as supplied by the industry) are tabulated in Tables 1 and 2 respectively.

Table 1 Geotechnical and physical properties of various materials

Property	Soil	Rice husk ash	Construction demolition waste	Lime
Specific gravity (ASTM D854–14 2014)	2.61	2.55	2.58	2.32
Physical appearance	Light brown	Dark gray	Light gray	White
Liquid limit (%) (ASTM D4318–10 2010)	50.8	38.3	–	–
Plastic limit (%) (ASTM D4318–10 2010)	27.3	NP	–	–
Plasticity index (%) (ASTM D4318–10 2010)	23.5	–	–	–
Coefficient of uniformity, C_u	–	–	1.66	–
Coefficient of curvature, C_c	–	–	0.74	–
Soil classification (ASTM D2487–11 2011)	CH	MI	SP	–
Optimum moisture content (%) (ASTM D698-07e1 2007)	16	29.8	13.3	–
Maximum dry density (g/cc) (ASTM D698-07e1 2007)	1.76	1.25	1.68	–
pH (ASTM D4972–18 2018)	6.7	7.8	8.1	11.2
Differential free swell (%) (IS 2720 Part 40 1977)	42	–	–	–

Construction demolition waste

The construction demolition waste (Fig. 1) is obtained from a broken cemented floor of a dismantled house in Hamirpur, Himachal Pradesh, India, and is passed through a 4.75-mm sieve after pulverizing it. The gradation curve of construction demolition waste reveals that the material lies in the category of poorly graded sand (SP) as shown in Fig. 2. The various geotechnical and chemical characteristics of construction demolition waste are tabulated in Tables 1 and 2 respectively.

Table 2 Chemical properties of various materials

Mineral	Clay (%)	Rice husk ash (%)	Lime (%)
Silicon dioxide (SiO_2)	51.28	87.54	2.10
Carbon (C)	–	5.70	2.20
Calcium oxide (CaO)	1.68	0.56	82.80
Magnesium oxide (MgO)	2.70	0.33	0.30
Calcium carbonate ($CaCO_3$)	–	–	4.30
Sodium oxide (Na_2O)	–	–	0.40
Sulfur trioxide (SO_3)	–	0.24	0.40
Aluminum oxide (Al_2O_3)	20.25	0.17	1.30
Ferric oxide (Fe_2O_3)	5.40	0.15	1.20
Potassium oxide (K_2O)	2.20	–	–
Titanium dioxide (TiO_2)	0.64	–	–
Sodium oxide (Na_2O)	0.22	–	–
Impurities	4.30	–	5.0
Loss on ignition at 800 °C	12.24	5.13	–

Lime

The lime (Fig. 1) used in the present study is purchased at a rate of 8 per kg from a local hardware vendor in Hamirpur, Himachal Pradesh, India. The lime was kept in a sealed container to avoid direct contact with the atmosphere and prevent the ingress of moisture. The various physical and chemical properties of lime are tabulated in Tables 1 and 3 respectively.

Results and discussions

Differential free swell

The differential free swell index is determined according to IS: 2720 (Part 40) 1977 and its value for clayey soil is 42%. The effect of the addition of RHA, CDW, and lime at varying percentages on clayey soil is shown in Fig. 3. The addition of RHA in varying amounts (4–20%) to clayey soil reduced the DFS value and became zero at 12% RHA; the further addition of RHA did not affect the DFS value. The reduction in DFS value on adding RHA may be due to the decrease in the specific surface, and also due to the replacement of clayey soil with non-swelling and pozzolanic material. The decrease in DFS value may be further attributed to higher silica content present in RHA and also due to the replacing of monovalent cations of clay with multivalent cations of RHA. A similar effect of reduction in DFS value on the addition of increasing RHA content to clayey soil is reported previously (Jain and Fuskele 2019). On adding CDW in varying amounts (12–28%) to clayey soil, the DFS value reduced to zero at 24% CDW content and further addition of CDW did not show

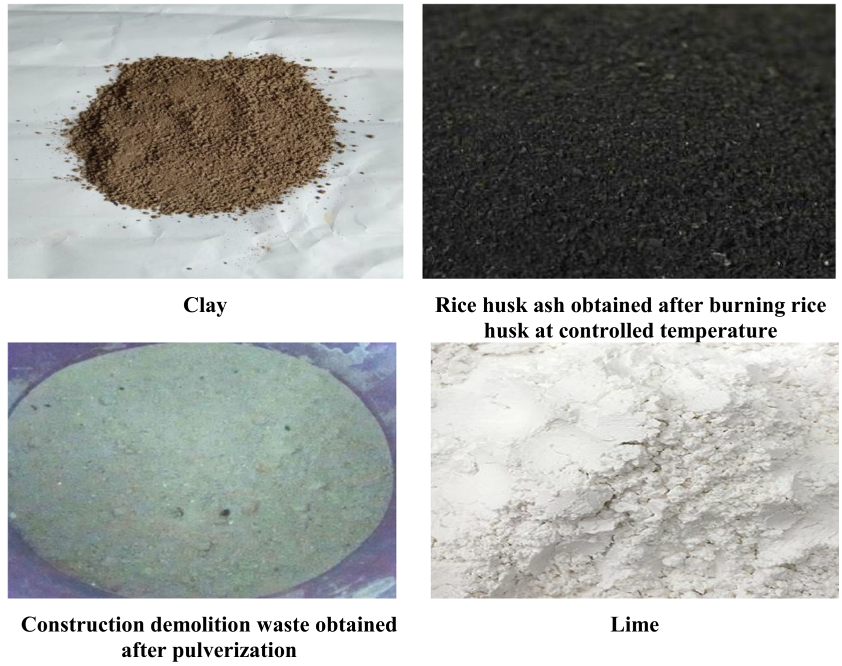

Fig. 1 Photos of materials used in the study

any change in DFS value. The reduction in DFS value on adding CDW may be due to the replacement of finer particles of clayey soil with coarser particles of CDW leading to the decrease in surface activity. The decrease in DFS value on adding CDW is reported by previous researchers as well (Sharma and Hymavathi 2016). On adding lime in varying content from 3 to 9%, the DFS value reduced and attained zero value at 5% lime content and further increment in lime content increased the DFS value. The reduction in DFS on adding lime to clayey soil may be due to the flocculation of clay particles with lime resulting in the reduced surface area thus decreasing the DFS value. The reduction in DFS value on adding lime to clayey soil is noticed by past researchers as well (Panjaitan 2014).

To evaluate the effect of the addition of lime mixed with RHA and CDW on DFS value, the optimum percentages of RHA (12%) and CDW (24%) are chosen and the lime content is varied accordingly. On adding lime in varying percentages (1, 3, and 5%) in a mixture of clay and RHA, the DFS value does not show any change up to 3% lime content and after that, it starts increasing (Fig. 4). The reduction in DFS may be attributed to the occurrence of granular material having non-swelling nature, whereas an increase in DFS beyond 3% lime content may be due to the reaction of free lime with water. On adding 1, 2, and 3% lime to a mixture of clay and CDW, the

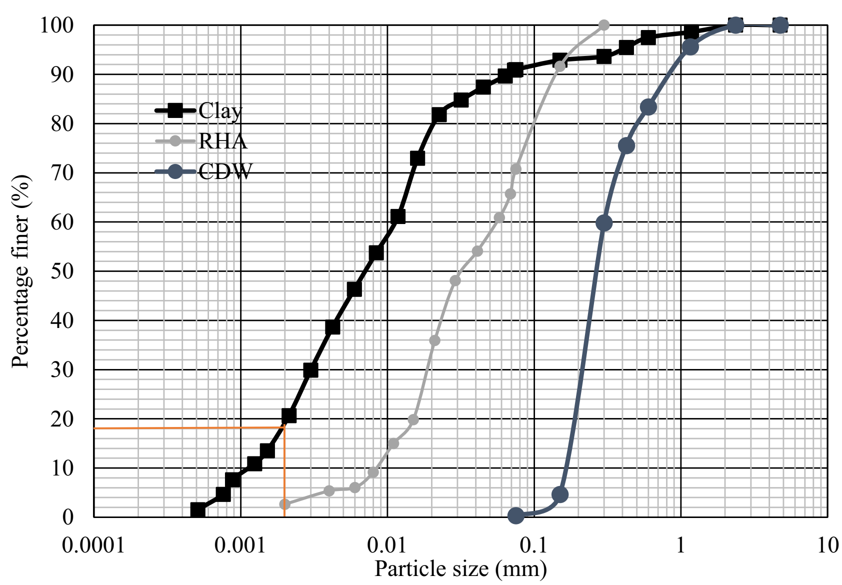

Fig. 2 Gradation curve of various materials

Table 3 Resilient modulus for various admixtures

Composition	Resilient modulus, Mpa
Clay: 100	18.00
Clay: RHA:: 88: 12	32.00
Clay: CDW:: 76: 24	45.00
Clay: lime:: 95: 5	84.02
Clay: RHA: lime:: 85: 12: 3	64.79
Clay: CDW: lime:: 75: 24: 1	73.00
Clay: RHA: CDW: lime:: 63:12: 24: 1	81.67

DFS value does not reveal any change up to 1% lime content and after that, it starts increasing (Fig. 4) which may be due to the occurrence of free lime which reacts with water and thus resulting in increased volume. These results are in good agreement with the results obtained earlier (Sharma and Hymavathi 2016). Thus, it is established from the results that the addition of RHA, CDW (both are waste materials), and lime (a costly material) reduces the DFS to zero at 12%, 24%, and 5% respectively. The results of combined materials reveal that optimized clay:RHA (12%) content reaches zero DFS at 3% lime content, whereas optimized clay:CDW (24%) reaches zero DFS at 1% cement content. The combined effect of the addition of optimum RHA (12%) and CDW (24%) along with varying lime content (1, 2, 3%) reveals that the DFS value is zero up to 1% addition of lime and after that, on increasing lime content, the DFS value also increased which may be due to the reaction of free lime with the water.

Based upon the above results, it can be inferred that the addition of an optimum amount of RHA and CDW along with 1% lime is best suited for reducing the swelling potential of clayey soils. If the choice is to be made from CDW and RHA then, CDW alone and CDW along with lime is best for reducing the swelling of the soils as higher amount of CDW and very less amount of lime is used. Moreover, CDW is available in abundant quantity all over the parts of the world whereas, RHA is not that much widely available and a higher quantity of lime is needed.

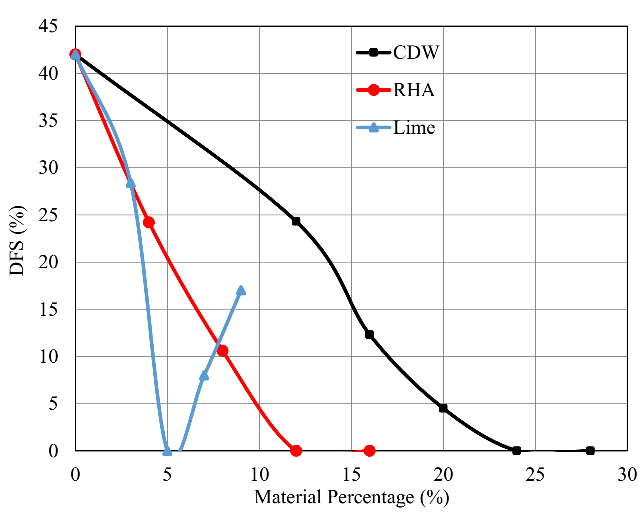

Fig. 3 Variation in the differential free swell of clay on adding various materials

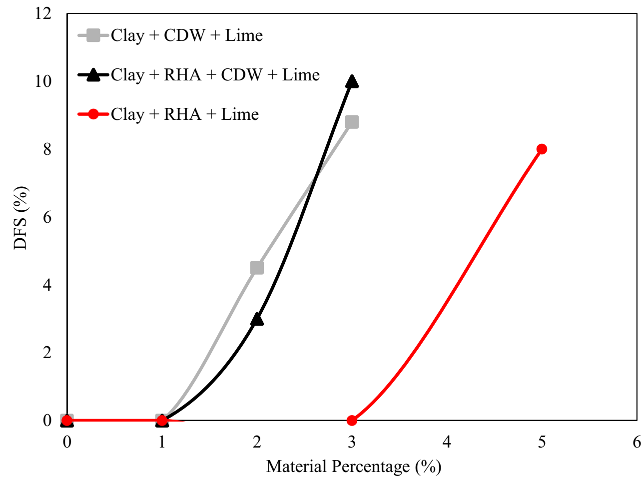

Fig. 4 Effect of adding lime on DFS of various optimum mixes

Compaction characteristics

The compaction characteristics of various mixes of clay:RHA, clay:CDW, clay:lime, clay:RHA:lime, and clay:CDW:lime are determined according to ASTM D698-07e1 (2007) and are presented in Figs. 5, 6, 7, 8, 9 and 10 respectively.

Clay: RHA mixture

On adding RHA to clayey soil in varying amounts, the MDD value reduces from 1.76 to 1.49 g/cm^3, and the OMC value increases from 16 to 23% at 12% RHA content. The further addition of RHA up to 16% shows a similar trend in MDD and

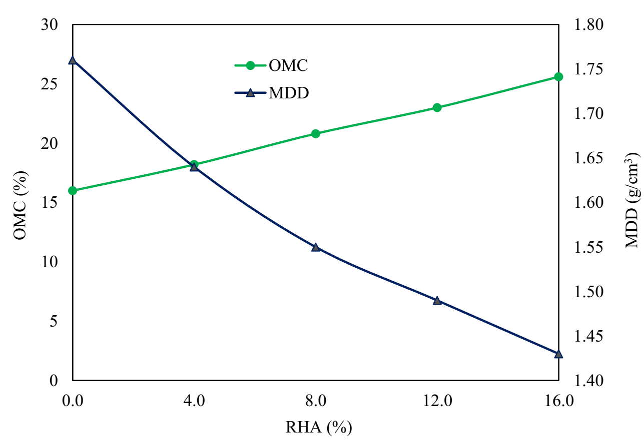

Fig. 5 Variation of OMC and MDD with varying RHA content in clayey soil

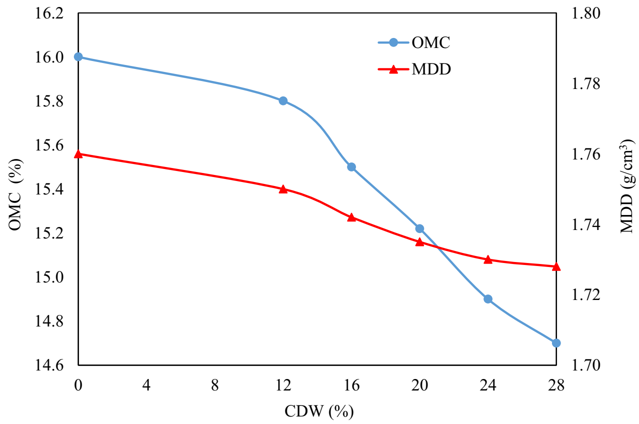

Fig. 6 Variation of OMC and MDD with varying CDW content in clayey soil

OMC values. The increase in OMC value on increasing RHA content may be due to the higher OMC value of RHA to that of clayey soil and also due to the increase in the percentage of fines (having larger specific surface) requiring more water; the reduction in MDD value may be due to the lower specific gravity of RHA to that of clayey soil and may also be due to the agglomeration of clay particles due to cation exchange thus increasing the volume. The results showing a reduction in MDD and an increase in OMC on adding RHA are in good agreement with previous researches (Choobbasti et al. 2010; Rahgozar et al. 2018).

Clay:CDW mixture

On increasing the CDW content in varying amounts from 12 to 28%, the MDD value decreases from 1.76 to 1.73 g/cm^3 and OMC value reduces from 16 to 14.9% at 24% CDW content. On further increasing CDW content to 28%, the same trend of variation is observed. The reduction in MDD value on increasing CDW content may be due to the aggregation of

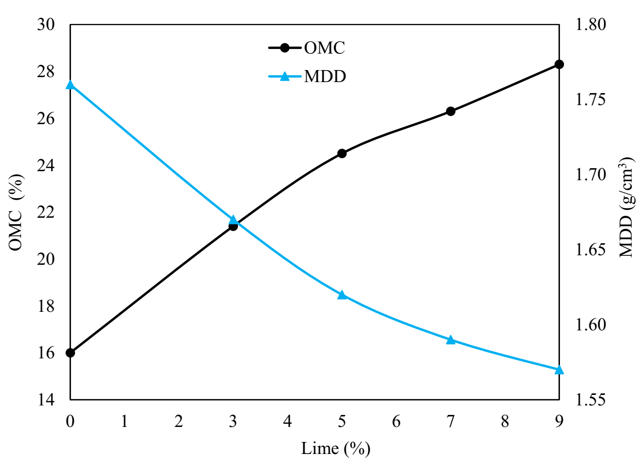

Fig. 7 Variation of OMC and MDD with varying lime content in clayey soil

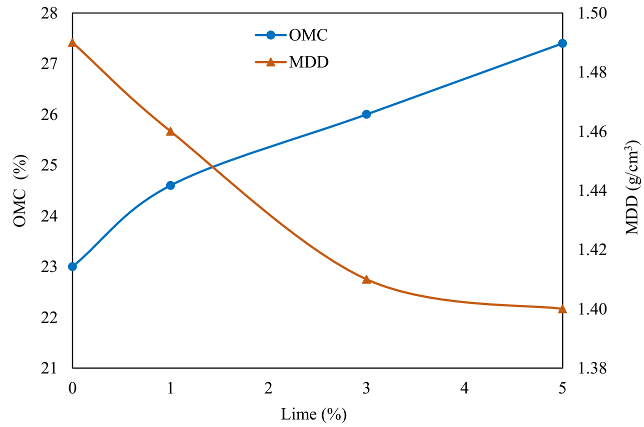

Fig. 8 Variation of OMC and MDD with varying lime content in clay:RHA mixture

clay:CDW mixture and also due to the lesser specific gravity of CDW than that of clay, whereas the reduction in OMC with increased CDW content may be due the lower specific surface of CDW than clay particles.

Clay:lime mixture

The addition of lime to clayey soil in varying amounts from 3 to 9% increases OMC from 16 to 24.5% and reduces MDD from 1.76 to 1.62 g/cm^3 on adding 5% lime. The further addition of lime to clayey soil shows the same type of variation in OMC and MDD. The further addition of clayey soil reveals a similar trend of MDD and OMC. The reduction in MDD value on adding lime may be due to the flocculation of clay particles on adding lime and also due to the lower specific gravity of lime. The improvement in OMC value is due to the pozzolanic reaction occurring between lime and clay particles. The results are in good agreement with the past few

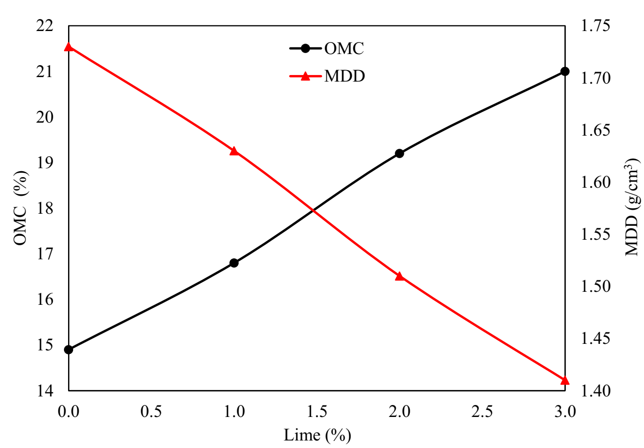

Fig. 9 Variation of OMC and MDD with varying lime content in clay:CDW mixture

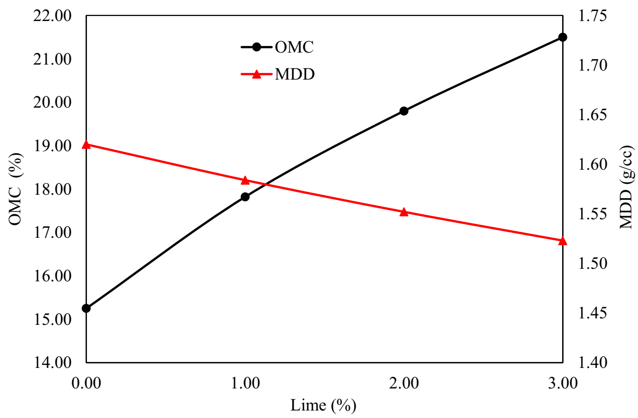

Fig. 10 Variation of OMC and MDD with varying lime content in Clay: CDW mixture

research works (Kavak and Akyarli 2007; Harichane et al. 2011; Bhardwaj and Sharma 2020).

Clay:RHA:lime mixture

The addition of lime in varying amount of 1, 3, and 5% in an optimized mix of clay and RHA (12%) shown in Fig. 8 reveals that the MDD value decrease from 1.49 to 1.41 g/cm^3 and the OMC value increases from 23 to 26% at 3% lime content. The reduction in MDD value on adding lime may be due to the flocculation of clay particles on adding lime and also due to the lower specific gravity of both lime and RHA compared to clay particles. The improvement in OMC value is due to the pozzolanic reaction occurring between lime and clay particles and also due to the higher OMC of RHA.

Clay:CDW:lime mixture

The addition of lime in varying amount of 1, 2, and 3% in an optimized mix of clay and CDW (24%) shown in Fig. 8 reveals that the MDD value decrease from 1.73 to 1.43 g/cm^3 and the OMC value increases from 14.9 to 21% at 1% lime content. The reduction in MDD value on adding lime may be due to the flocculation of clay particles on adding lime and also due to the lower specific gravity of both lime and CDW compared to clay particles. The improvement in OMC value is due to the pozzolanic reaction occurring between lime and clay particles.

Clay:RHA:CDW:lime mixture

The addition of lime in varying amount of 1, 2, and 3% in an optimized mix of clay, RHA (12%), and CDW (24%) shown in Fig. 10 reveals that the MDD value further decreases to 1.62 g/cm^3 and the OMC value increases to 17.80% at 1% lime content. The reduction in MDD value on adding lime in clay + RHA + CDW mixture may be due to the flocculation of clay particles on adding lime and also due to the lower specific gravity of lime, RHA and CDW compared to clay particles. The improvement in OMC value is due to the pozzolanic reaction occurring between lime and clay particles and also due to the higher OMC of RHA possessing finer particle with the larger specific surface.

Unconfined compressive strength tests

The unconfined compressive strengths for curing period of 3, 7, and 28 days for various mixes of clay:RHA, clay:CDW, clay:lime, clay:RHA:lime, clay:CDW:lime, and clay:RHA:CDW:lime are determined according to ASTM D2166 (2013) and are presented in Figs. 11, 12, 13, 14, 15 and 16 respectively.

Clay:RHA mixture

The UCS value of clayey soil after 3 days is 105 kN/m^2 which increases to 284, 382, and 425 kN/m^2 on adding 8, 12, and 16% RHA content. The 7-day UCS of clayey soil is 303 kN/m^2 which increases to 548, 667, and 714 kN/m^2 on adding 8, 12, and 16% RHA content (Fig. 11). The 28-day UCS of clayey soil is 728 kN/m^2 which increases to 904, 1064, and 1089 kN/m^2 on adding 8, 12, and 16% RHA content. The increase in UCS value on adding RHA may be due to the pozzolanic reaction between RHA and clay particles and also may be due to the frictional resistance offered by RHA particles. A similar increase in UCS value on adding RHA has been reported earlier (Ashango and Patra 2016; Liu et al. 2019).

Clay:CDW mixture

The UCS value of clayey soil after 3 days is 105 kN/m^2 which increases to 305, 489, 514, and 621 kN/m^2 on the addition of

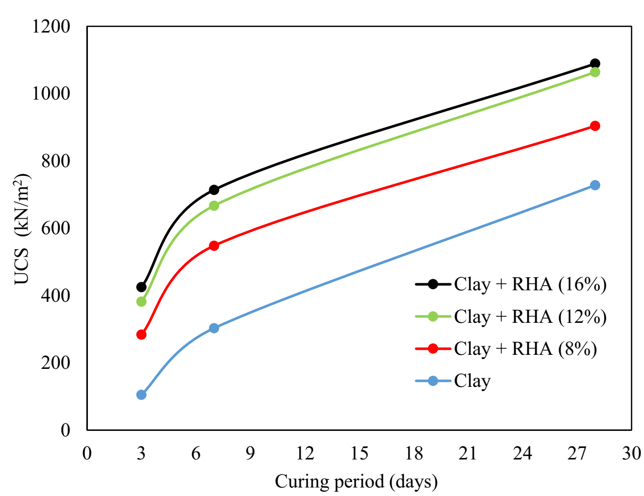

Fig. 11 UCS versus curing period for varying RHA in clayey soil

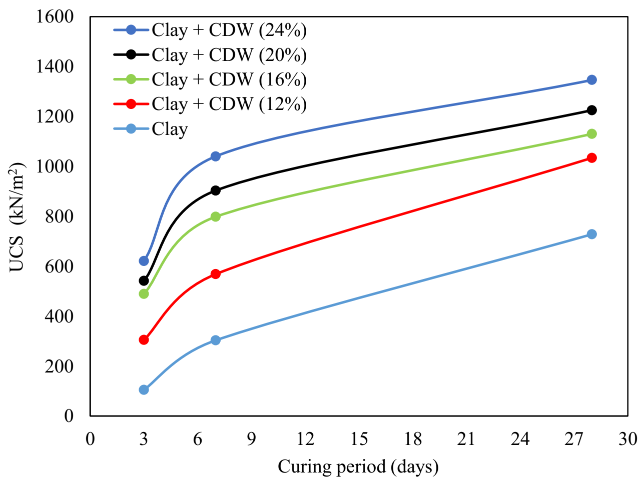

Fig. 12 UCS versus curing period for varying CDW in clayey soil

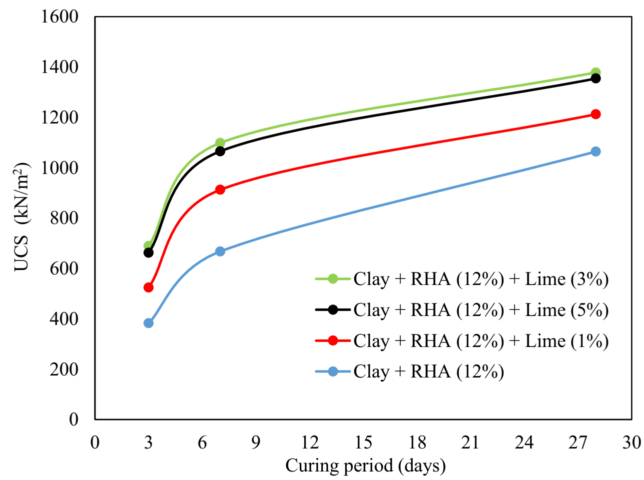

Fig. 14 UCS versus curing period for varying lime in clay:RHA mixture

12, 16, 20, and 24% CDW content respectively (Fig. 12). The 7-day UCS of clayey soil is 303 kN/m^2 which increases to 568, 798, 903, and 1040 kN/m^2 on adding 12, 16, 20, and 24% CDW content respectively. The 28-day UCS of clayey soil is 728 kN/m^2 which increases to 1034, 1130, 1225, and 1346 kN/m^2 on adding 12, 16, 20, and 24% CDW content respectively. This reveals that the addition of CDW to clayey soil increases the UCS of the mix which may be attributed to the pozzolanic reaction occurring between CDW and soil particles. A similar trend of increase in UCS of clay:CDW mixture has been reported in past studies (Sharma and Hymavathi 2016).

Clay:lime mixture

The UCS value of clayey soil after 3 days is 105 kN/m^2 which increases to 412 and 518 kN/m^2 on adding 3 and 5% lime respectively and reduced to 497 kN/m^2 on adding 7% lime content (Fig. 13). The 7-day UCS of clayey soil is 303 kN/m^2 which increases to 808 and 925 kN/m^2 on adding 3 and 5% lime respectively and reduced to 895 kN/m^2 on adding 7% lime content. The 28-day UCS of clayey soil is 728 kN/m^2 which increases to 1135 and 1274 kN/m^2 on adding 3 and 5% lime respectively and reduced to 1255 kN/m^2 on adding 7% lime content. This reveals that on adding lime in increasing amount, the UCS value increases constantly but the rate of increase is very less beyond 5% lime content and hence, 5% lime content may be chosen as optimum content. The increase in UCS value on adding lime may be due to the chemical reaction occurring between soil and lime particles. A similar increase in UCS value on adding lime to clay has been reported earlier (Dash and Hussain 2012; Asgari et al. 2015; Bhardwaj and Sharma 2020).

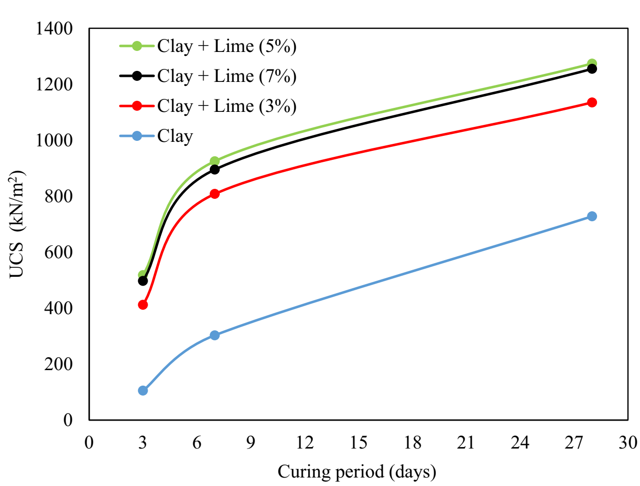

Fig. 13 UCS versus curing period for varying lime in clayey soil

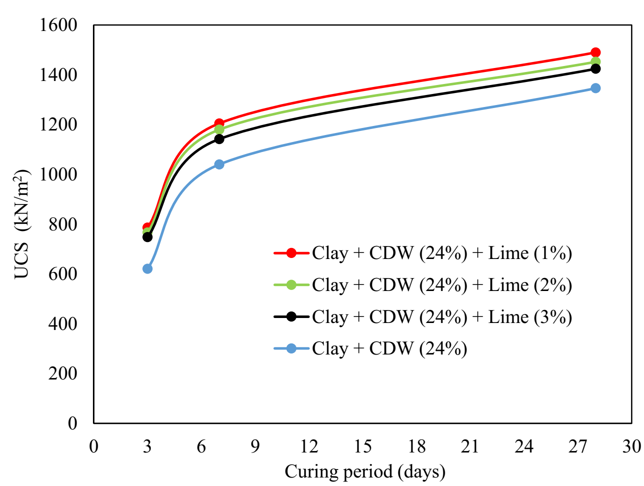

Fig. 15 UCS versus curing period for varying lime in clay:CDW mixture

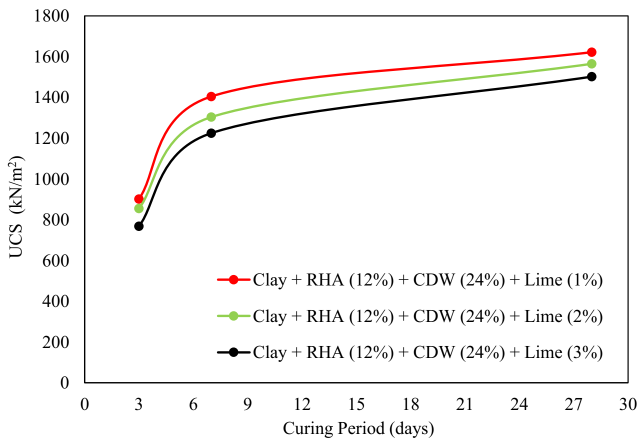

Fig. 16 UCS versus curing period for varying lime in clay:RHA:CDW mixture

Clay:RHA:lime mixture

The UCS value of optimum clay: RHA (12%) soil after 3 days is 382 kN/m^2 which increases to 524 and 689 kN/m^2 on adding 1 and 3% lime respectively and decreases to 662 kN/m^2 on adding 5% lime content (Fig. 14). The 7-day UCS of clayey soil is 667 kN/m^2 which increases to 912 and 1098 kN/m^2 on adding 1 and 3% lime respectively and decreases to 1065 kN/m^2 on adding 5% lime content. The 28-day UCS of clayey soil is 1064 kN/m^2 which increases to 1212 and 1378 kN/m^2 on adding 1 and 3% lime respectively and decreases to 1354 kN/m^2 on adding 5% lime content. Thus, it is established that 3% lime may be taken as optimum content for optimized clay:RHA (12%) mixture. The increase in the UCS value of clay:RHA mixture on adding lime may be due to the pozzolanic reaction occurring between clay:RHA content and lime particles. A similar increase in UCS value on adding RHA and lime together to clay has been reported earlier (Ashango and Patra 2016).

Clay:CDW:lime mixture

The UCS value of optimum clay:CDW (24%) soil after 3 days is 621 kN/m^2 which increases to 786 kN/m^2 on adding 1% lime and further decreases to 767 and 748 kN/m^2 on adding 2 and 3% lime content respectively (Fig. 15). The 7-day UCS of clayey soil is 1040 kN/m^2 which increases to 1205 kN/m^2 on adding 1% lime and further decreases to 1180 and 1142 kN/m^2 on adding 2 and 3% lime content respectively. The 28-day UCS of clayey soil is 1346 kN/m^2 which increases to 1490 kN/m^2 on adding 1% lime and further decreases to 1452 and 1424 kN/m^2 on adding 2 and 3% lime content respectively. Thus, it is established that 1% lime may be taken as optimum content for optimized clay:CDW (24%) mixture. The increase in the UCS value of clay:CDW mixture on adding lime may be due to the chemical reaction occurring between clay:CDW content and lime particles. A similar increase in UCS value on adding CDW and lime together to clayey soil has been reported earlier (Sharma and Hymavathi 2016).

Clay:RHA:CDW:lime mixture

The effect of addition of RHA, CDW, and lime altogether on unconfined compressive strength of clayey soil reveals an increase in unconfined compressive strength for all curing periods (Fig. 16). The addition of 1% lime shows the highest UCS values for all curing periods and the highest value is obtained for 28 days of curing period as 1622 kN/m^2. On further increasing the lime content beyond 1%, the UCS value decreases. This establishes that 1% of lime is sufficient to increase the UCS value of optimum clay:RHA:CDW:lime composite. The increase in the UCS value of clay:RHA:CDW mixture on adding lime may be due to the pozzolanic reaction occurring between clay:RHA:CDW content and lime particles.

California bearing ratio tests

The CBR tests are performed on clay and optimum mixes of RHA, CDW, and lime alone and in combination according to ASTM D1883–05 2005 standards and plots are shown in Fig. 17. The soaked CBR value of clayey soil is 1.80% revealing that the clayey soil cannot be directly used in sub-grade of pavements (CBR value of 5% is at least required for the design of low volume traffic roads according to IRC-SP-77 2008). On adding 12% RHA to clayey soil, the soaked CBR value increases from 1.8 to 3.2% and may be due to the interlocking of the coarser particles and variation in the cohesive nature of the clay and RHA mixture. This reveals that CBR is still too low to be used as sub-grade material. Similar behavior was observed by several researchers (Choobbasti et al. 2010; Karatai et al. 2017; Rahgozar et al. 2018). On adding 24% CDW to clayey soil, the soaked CBR value of the composite increases from 1.8 to 4.5% which may be due to the existence of sand in CDW thus helping in mobilizing the angle of shearing resistance leading to an increase in the strength; but this value is too not adequate to be used as material to be used in sub-grade. Similar behavior on adding CDW to clayey soil was reported earlier (Sharma and Hymavathi 2016). On adding 5% lime to clayey soil, the soaked CBR value of the composite increases from 1.8 to 11.5% (5.38 times more) which is quite adequate to be used as sub-grade material for pavement design and may be due to cation exchange reaction between soil and lime resulting in the binding of soil particles. A similar behavior showing an increase in CBR on the addition of lime to clay was observed by several researchers (Kavak and Akyarli 2007; Panjaitan 2014). The addition of 3% lime content in optimum clay:RHA mix increases the CBR value from 3.2 to 7.8%; the addition of 1% lime content to clay:CDW mix increases the CBR value from 4.5 to 9.4%; the addition of 1% lime to clay:RHA:CDW mix increases the

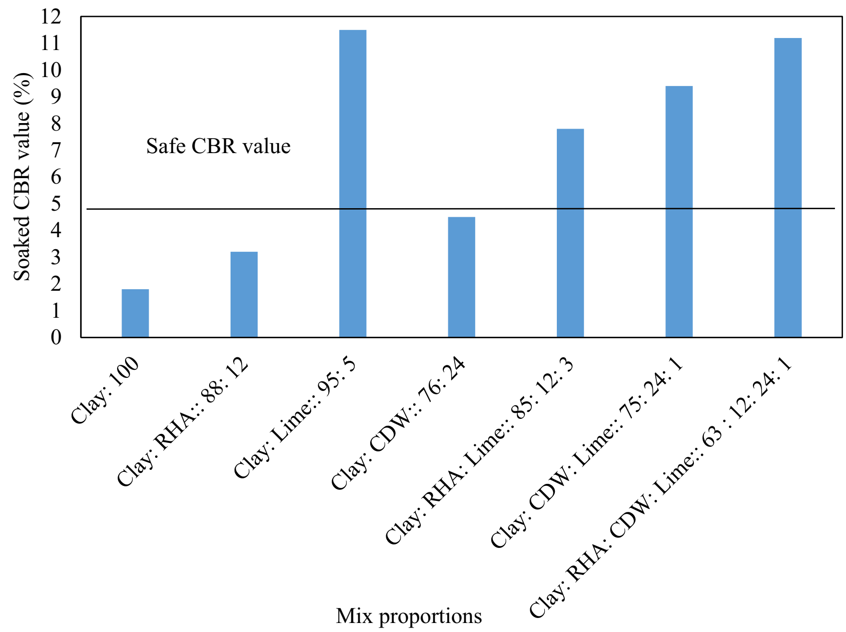

Fig. 17 CBR values for various mixes

CBR value to the highest 11.2%. This reveals that on adding lime to optimum mixes of clay:RHA, clay:CDW, and clay:RHA:CDW mixture, the CBR value attained is quite sufficient to be used as sub-grade material. Based on the CBR results, it can be established that lime alone and along with RHA and CDW can be used for the design of low-volume traffic pavements. The results reveal that the CBR value is the highest for clay:lime combination followed by clay:RHA:CDW:lime and clay:CDW:lime and further followed by clay:RHA:lime mixture. Considering the economy, soil mixed with lime alone cannot be used as sub-grade material as it will prove to be very costly. RHA and CDW being waste materials can be used along with lime and are best suited as sub-grade material considering the economy and from the environmental conservation point of view. Along with this, the disposal problem of both the waste materials can be solved by using them in sub-grade along with suitable percentages of lime. The best mix which is obtained on the basis of CBR value to be used as sub-grade material is clay:RHA:CDW:lime:: 63:12:24:1 as the highest amount of waste and lower amount of lime is used in this mixture, thus solving the haphazard problems of wastes to a larger extent. Out of these two materials, the percentage of lime in clay:CDW mix (only 1% lime) is much lower than that of clay:RHA (3% lime) and higher amount of waste (24% CDW compared to that of 12% RHA) is used, thus making it more economical and eco-friendly. Moreover, CDW is available in abundant quantities all over the world whereas RHA is only available where rice processing mills exist. This establishes that the mixture of clay:CDW:lime is best suited for the design of sub-grade pavements followed by clay:RHA:lime and clay:lime mix.

Determination of resilient modulus of sub-grade

The behavior of the sub-grade is essentially elastic under the transient traffic loading with negligible permanent deformation in a single pass. Resilient modulus is the measure of its elastic behavior determined from recoverable deformation in the laboratory tests. The modulus is an important parameter for the design and performance of a pavement. It is a measure of material stiffness and provides a parameter to analyze the stiffness of materials under different conditions, such as moisture, density, and stress level. Since pavement life and surface deflection are strongly related to each other, resilient modulus is a fundamental and rational material property that needs to be included in the pavement design. The resilience modulus is calculated according to IRC 37:2012 2012 as follows:

M_R (MPa) = 10.0 * (CBR) for CBR ≤ 5.

M_R (MPa) = 17.6 * $(CBR)^{0.64}$ for CBR > 5.

The values of resilience modulus for various mixes shown in Table 3 reveal that there is an increase in resilience modulus on stabilizing the clayey soil using various admixtures.

Thickness of flexible pavement

Plates 1–8 of IRC 37:2012 2012 are used for the design of thickness of flexible pavements consisting of granular base and granular sub-base layers. The design calculations are performed for different traffic loads of 10, 50, 100, and 150 million standard axles (msa) based on CBR values. Generally, the CBR value greater than 5% is recommended for the design of the thickness of flexible pavements. The various values of pavement thickness obtained from codal

Table 4 Pavement thickness for various mixes

Composition	Pavement thickness (mm) for cumulative traffic (msa)					
	2	5	10	50	100	150
Clay: 100	–	–	–	–	–	–
Clay: RHA:: 88: 12	335	335	380	380	380	380
Clay: CDW:: 76: 24	265	285	330	330	330	330
Clay: lime:: 95: 5	150	150	200	200	200	200
Clay: RHA: lime:: 85: 12: 3	150	150	200	200	200	200
Clay: CDW: lime:: 75: 24: 1	150	150	200	200	200	200
Clay: RHA: CDW: lime:: 63:12: 24: 1	150	150	200	200	200	200

provision for various mixes are tabulated in Table 4. It is clear from the results that there is a reduction in pavement thickness on stabilizing the clayey soil with various admixtures. The reduced pavement thickness is the same for clay:lime, clay:RHA:lime, clay:CDW:lime, and clay:RHA:CDW:lime mixtures. Out of these four mixtures, the mix containing clay:RHA:CDW:lime is best suited for the design of pavement as the highest amount of waste material (RHA (12%) and CDW (24%) = 36%) and a very lesser amount of costlier material (lime = 1%) is used.

Conclusions

Based upon the interpretation of laboratory test results on the study of the effect of agricultural and constructional waste along with lime on geotechnical characteristics of clayey soil, the following conclusions are drawn:

1. The addition of 12% rice husk ash, 24% construction demolition waste, and 5% lime individually reduce the differential free swell to zero. The addition of 3% lime to optimum content of clay:rice husk ash (12%) and 1% lime optimum clay:construction demolition waste (24%) and clay:rice husk ash(12%): construction demolition waste (24%) respectively reduce differential free swell to zero. On increasing percentages of rice husk ash and construction demolition waste beyond optimum value, the differential free swell does not change; however, on increasing the percentage of lime alone and in combination with other materials, the differential free swell increases due to swelling of soil.
2. On adding rice husk ash, construction demolition waste, and lime alone and in combination, the maximum dry density decreases; however, the reduction is less in the case of clay:construction demolition waste followed by clay:construction demolition waste:lime, clay:lime, clay:rice husk waste:construction demolition waste:lime, clay:rice husk ash, and clay:rice husk ash:lime.
3. On adding rice husk ash and lime alone, the optimum moisture content increases whereas on adding construction demolition waste alone to clayey soil, the optimum moisture content decreases. On adding lime to optimum clay:rice husk ash and clay:construction demolition waste, the optimum moisture content further increases; the increase is higher for clay:rice husk ash:lime mixture.
4. On adding rice husk ash, construction demolition waste and lime (up to 5%) individually, the unconfined compressive strength increases for all curing periods, the increase being the highest for clay:construction demolition waste mixture followed by clay:lime and clay:rice husk ash mixtures. The combination of clay:rice husk ash:construction demolition waste:lime gives the highest strenght followed by clay:construction demolition waste (24%):lime (1%) and clay:rice husk ash (12%):lime (3%) mixture. Thus, a combination of both the wastes and lime is best suited for the enhancement in unconfined compressive strength.
5. The soaked CBR results indicate that the combination of clay:lime (5%) attains the highest CBR value followed by clay:rice husk ash (12%):constructuon demolition waste (24%):lime (1%), clay:construction demolition waste (24%):lime (1%), clay:rice husk ash (12%):lime (3%), clay:construction demolition waste (24%), and clay:rice husk ash (12%) mixture. The best combination for the design of low volume roads is clay:RHA (12%):construction demolition waste (24%):lime (1%) for which very little amount of lime (costly material) and higher amounts of waste material is used.
6. With the addition of various admixtures, the resilient modulus increases revealing the improvement in elastic properties of sub-grade materials. The pavement thickness reduces considerably on adding various admixtures to clayey soil thus minimizing the cost of the pavement.
7. The detailed study carried out by mixing agricultural and industrial waste along with lime to clayey soil indicates that these materials can be effectively used for reducing differential free swell and pavement thickness and for

increasing unconfined compressive strength and California bearing ratio. Regarding the choice of the material to be used, the first preference may be given to the use of construction demolition waste along with lime as it is available in ample amounts throughout the world. The areas where rice ash is produced on a large scale, using rice husk ash along with lime, are a vital option to minimize its adverse effects on the environment.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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