MATERIALS PHYSICS AND MECHANICS RESEACH ARTICLE

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Laboratory study on use of lime and waste materials in improving geotechnical properties of clay

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ABSTRACT

The waste materials such as fly ash, construction demolition waste, and plastic waste are generated in tremendous quantities and are dumped haphazardly thereby causing irreparable damage to the environment. Proper utilization of these wastes particularly in the construction sector will protect the environment from their harmful effects and will prove to be economical through the preservation of precious natural resources. This paper presents an investigation on the utilization of lime, fly ash, and construction demolition waste individually and in combination with each other for the stabilization of poor soil. The utilization of plastic waste along with soil-fly ash-construction demolition waste-lime composite was further investigated. The samples for unconfined compressive strength and split tensile strength were compacted at optimum moisture content to maximum dry density, which was obtained from standard Proctor compaction tests. The samples were tested after 7 days, 28 days, and 56 days of curing periods. The results reveal that the addition of admixtures increases the unconfined compressive strength and split tensile strength, and the optimum mixes were selected based on 7 days of unconfined compressive strength. The increase in strength with the addition of admixtures depends on the type of admixture used and the formation of new minerals, which can be observed from XRD graphs. The soaked California bearing ratio tests were conducted on the optimum mixes and soil-fly ash-C&D waste-lime mix was selected as the best sub-grade material compared to other material combinations based upon economic and environmental considerations.

KEYWORDS

clay • fly ash • construction demolition waste • lime • plastic waste

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Introduction

The production of waste materials is increasing day by day, resulting in the requirement of a large area for disposal, which is a costly affair. The utilization of waste materials in improving the properties of soil is one of the effective methods of disposal. The waste materials used in this study are fly ash, construction demolition (C&D) waste, and plastic waste. Fly ash is a waste material produced by thermal power plants. Though the use of fly ash is growing continuously, much attention is needed to utilize more and more quantity of fly ash. Rapid infrastructure development leads to an increase in the generation of C&D waste in large quantities, the disposal of which is causing environmental and economic problems. Most of C&D waste remains unutilized hence, using this waste in improving the properties of the soil will be useful both from an economical and eco-friendly point of view. Plastic waste is produced in different ways such as shopping bags, polypropylene of plastic sacks, polypropylene of carpets, and plastic bottles. Although, the reuse and recycling of plastic waste are getting attention day by day, even then only a small percentage of the total volume of plastic waste produced is being utilized and a larger amount of it is placed in disposal sites or storage. The construction of disposal sites and/or landfills will be a costly process, hence, disposal of plastic by using it in soil stabilization is one of the viable options. Soil stabilization is the process of improving the engineering and index properties of poor soils. Numerous research studies have been conducted in the past to stabilize expansive soils by using various materials and admixtures [1–4]. Though lime is not a waste material and is costly but can be utilized in soil stabilization because it leads to early and high strength gain. Thus, fly ash, C&D waste, plastic waste, and lime are chosen as stabilizing materials for improving the properties of soil.

Some research has been done on the utilization of these materials in soil stabilization. Adding the fly ash to the soil improves the engineering properties i.e. unconfined compressive strength (UCS) and California bearing ratio (CBR) of soil and is cost-effective material [5–8]. The uniaxial compression indirect (splitting) tension and flexure strength were also found to be enhanced with the addition of fly ash [5]. There is a decrease in the maximum dry density (MDD) and an increase in the value of optimum moisture content (OMC) on adding fly ash to soil [6,7]. The various properties of soil such as plasticity index, free swell, activity, swelling pressure, swell potential, etc. are found to be decreased with the addition of fly ash or fly ash-lime content [8].

Many researchers explained the consequences of lime on the engineering properties of soil, some among them are: The characteristics such as swell potential, liquid limit, plastic limit, free swell, cohesion, compaction characteristics, and modulus of elasticity are affected by the addition of lime to soil [9–14]. There is an improvement in the value of OMC, CBR value, and UCS of the mix due to the addition of lime to soils [9,11,12,14]. This is attributed to the formation of cementing minerals such as calcium aluminate hydrate (CAH), calcite, and mullite which are identified by X-ray diffraction (XRD) [10,12,13]. Initially, with the increase in lime content up to 5 %, there is an increase in the plastic limit and a decrease in the liquid limit, but beyond 5 % lime content, the Atterberg limits show negligible variations. Further, there is a decrease in the swell potential up to certain lime content, after which it accelerates its value beyond 9 and 5 % addition of lime for coarse-grained soils and fine-grained soils respectively. The unconfined compressive strength (UCS) of the composite mix increases up to a certain lime content [13].

Construction demolition waste refers to the waste generated during the demolition of structures. A lot of research in the past have been conducted in past on the utilization of recycled aggregates from concrete waste in soil stabilization and as sub-base and base course material in pavements [15–25]. Many researchers concluded that for unpaved rural roads, natural aggregates can be replaced by recycled aggregates obtained from C&D waste [19,22]. Soils blended with fine crushed concrete cubes and cement showed considerable improvement in UCS value, split tensile strength (STS), and CBR value as shown in [20].

The plastic waste when added to soil increases the peak strength, ultimate strength; energy absorption capacity, and UCS value [26,27]. Sub-grade characteristics of soil are improved with the addition of plastic waste because of an increase in CBR value [28–30]. The addition of plastic waste increases deviator stress and changes the behavior from brittle to ductile and the penetration resistance increases with plastic waste as shown in [30].

When fly ash and lime are added in combination to poor soils, OMC, UCS, and CBR values are found to be increased whereas MDD value and the free swell were observed to be decreased which was resulted due to the flocculation and cation exchange reaction [31–33].

The use of fly ash for agricultural purposes has been studied and the existence of harmful trace elements such as Pb, Cd, Ni, etc. has been shown [34]. Further, class F fly ash alone pollutes the groundwater thereby damaging the environment but if class F fly ash is used with lime, the release of harmful metals can be prevented as shown in [35].

The addition of plastic waste to the soil-fly ash-lime mix increases the UCS value, split tensile strength, and overall toughness [36–40]. The addition of plastic waste or fiber increases the CBR value and changes the failure behavior from brittle to ductile [41–47]. Thus, the soil-fly ash-lime-plastic waste mix can be effectively utilized in geotechnical and pavement applications.

The primary objective of this paper is to reveal how waste materials such as fly ash, C&D waste, plastic waste, and lime can be used in refining the properties of soil and to investigate the strength characteristics of various material combinations such as clay-fly ash, clay-C&D waste, clay-lime, clay-fly ash-lime, clay-C&D waste-lime, clay-fly ash-C&D waste, clay-fly ash-C&D waste-lime, clay-fly ash-C&D waste-lime-plastic waste mixtures for obtaining the optimum composite in soil stabilization. Further, the use of fly ash with lime can prevent the release of harmful trace elements present in it thus minimizing the negative impact on the environment.

Experimental study

The soil (S) used in the current study was brought from a construction site near Hamirpur, Himachal Pradesh (India). The fly ash (FA) was collected from Ropar thermal power plant and construction demolition (C&D) waste was acquired from the floor finish layer of local construction. The standard specification [45] for quicklime and hydrated lime was followed for use of lime in soil stabilization.

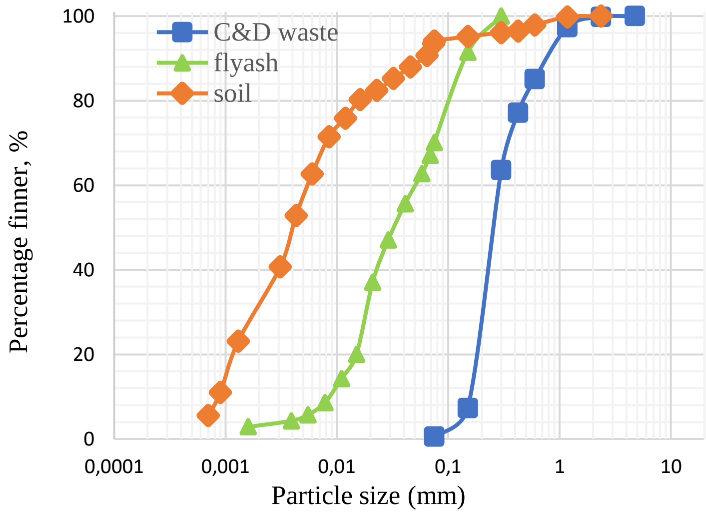

Fig. 1. Gradation curves of soil, fly ash and C&D waste

The plastic waste used in the present investigation was obtained from wasted online shopping bags, which were cut into pieces 12 mm in length and 6 mm in width. The average thickness of the plastic bags was 70 µm. The particle size curves of soil, fly ash, and construction demolition waste is shown in Fig. 1 [48–50]. Based on the Indian soil classification system as per [51], the soil was classified as clay with high plasticity, CH. The composition of fly ash lies in the range of the class F category. The gradation curve of C&D waste reveals that most of the particles are in the fine sand range. The properties of soil, fly ash and C&D waste are shown in Tables 1–3 respectively.

Table 1. Properties of soil

Properties	Value
Natural water content, w_n, %	22.0
Specific gravity *G* [52]	2.573
Liquid limit w_L, %	51.0
Plastic limit w_p, %	23.0
Plasticity index (PI), %	28.0
Soil classification	CH
Maximum dry density ρ_d, KN/m^3	17.5
Optimum moisture content, %	16.0
Percent finer than 2 µm, %	32
Coefficient of permeability, cm/s [53]	3.337×10^{-8}
Unconfined compressive strength after 7 days, KN/m^2	355.05
Differential free swell, % [54]	16.52
Soaked California bearing ratio, %	1.612

Table 2. Properties of fly ash

Chemical composition and index properties	Value
Silica (SiO_2), %	59.50
Alumina (Al_2O_3), %	27.10
Iron oxide (Fe_2O_3), %	7.36
Calcium oxide (CaO), %	2.30
Magnesium oxide (MgO), %	0.64
Sulphur trioxide (SO_3), %	0.85
Loss of ignition, %	2.25
Specific gravity, *G* [52]	1.966
Liquid limit, w_L (%)	39.5
Coefficient of uniformity, C_u	4.909
Coefficient of curvature, C_c	0.930
Indian standard soil classification	MI
Optimum moisture content, %	27.4
Maximum dry density ρ_d, KN/m^3)	12.24
Coefficient of permeability, cm/s [53]	6.6×10^{-5}
Soaked California bearing ratio, %	4.45

Table 3. Properties of construction demolition waste

Properties	Value
Specific gravity, *G* [52]	2.57
Coefficient of uniformity C_u	1.781
Coefficient of curvature C_c	0.877
Soil classification	SP
Optimum moisture content, %	12.4
Maximum dry density, ρ_d, KN/m^3	16.75
Coefficient of permeability, cm/s [53]	4.26×10^{-4}
Soaked California bearing ratio, %	17.07

Various tests were performed to classify the best optimum mix and best optimum arrangement for the stabilization of clayey soil. Firstly, the standard Proctor compaction tests were conducted on soil-fly ash mixes, soil-lime mixes, soil-C&D waste mixes, soil-fly ash-lime mixes, soil-C&D waste-lime mixes, soil-fly ash-C&D waste mixes, soil-fly ash-C&D waste-lime mixes and soil-fly ash-C&D waste-lime-plastic waste mixes as per standard [55]. The results of the compaction tests detailing MDD and OMC are shown in Table 4. Based on the results, it can be concluded that the optimum mixes cannot be obtained from compaction characteristics.

Table 4. Compaction characteristics of different mixes

Mix proportions	Maximum dry density, KN/m^3	Optimum moisture content, %
S :: 100	17.50	16.00
S:FA:: 92:8	16.98	16.70
S:FA :: 88:12	16.92	16.80
S:FA :: 84:16	16.90	17.10
S:L :: 97:3	16.85	18.00
S:L :: 96:4	16.68	19.00
S:L :: 95:5	16.41	19.50
S:C&D :: 88:12	17.32	15.10
S:C&D :: 78:22	17.22	14.95
S:C&D :: 76:24	17.20	14.90
S:FA:L :: 85.8:11.7:2.5	15.90	20.00
S:FA:L :: 84.92:11.58: 3.5	15.82	20.40
S:FA:L :: 84.04:11.46:4.5	15.81	20.90
S:C&D:L :: 77.62:21.89:0.49	17.04	17.00
S: C&D:L :: 77.42:21.836:0.744	16.86	17.60
S: C&D:L :: 77.23:21.78:0.99	16.78	19.00
S: FA:C&D :: 66:17:17	16.61	17.00
S: FA:C&D :: 65:17:18	16.63	16.80
S: FA:C&D :: 64:18:18	16.62	17.50
S: FA:C&D:L:: 64.36:16.83:17.82: 0.99	16.26	19.00
S:FA:C&D: L :: 63.73:16.67:17.64:1.96	15.96	19.40
S:FA:C&D: L :: 63.12:16.5:17.47:2.91	15.80	19.80
S: FA:C&D:L:PW :: 64.25:16.79:17.78:0.98:0.2	15.96	18.60
S:FA:C&D:L:PW :: 64.11:16.76:17.75:0.98:0.4	16.08	18.60
S:FA:C&D:L: PW :: 63.97:16.73:17.72:0.98:0.6	16.03	18.60

To demonstrate the effect of C&D waste on the liquid limit of soil, tests were piloted on soil alone and on soil C&D waste mixes, as per [56]. The results of the liquid limit test are shown in Fig. 2, which designates that the liquid limit falls down with the increase in the content of C&D waste. As the percentage of C&D waste approaches 30 %, the lowering rate in liquid limit also falls down, which indicates that the optimum mix should contain between 20-30 % of C&D waste. As the liquid limit is one of the important parameters in selecting the sub-grade material, it can be established from liquid limit tests that adding C&D waste to soil can improve the performance of soil as pavement sub-grade material.

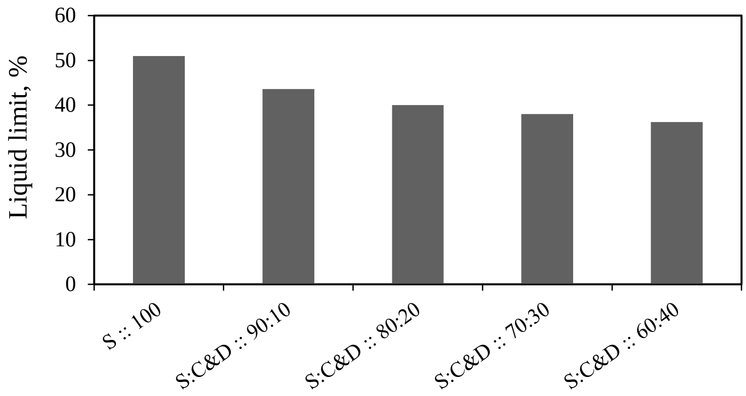

Fig. 2. Influence of addition of construction demolition waste on liquid limit of soil

The unconfined compressive strength tests were performed on numerous mix proportions to obtain the optimum composite mixes. The compaction of samples having a size of 38 mm diameter and 76 mm height was done to MDD in a standard mold at OMC. In order to avoid excess moisture loss, samples were kept in desiccators for 7, 28, and 56 days curing periods, and UCS tests were performed on these samples as per standard [57]. Two samples were prepared for every mix combination for each curing period and an average of two is presented as the UCS value. The optimum mix was chosen for that mix proportion which yielded the highest UCS value.

The split tensile strength tests were conducted as per [58] in split mold on samples of 50 mm diameter and 25 mm height prepared in a standard mold at OMC compacted to MDD. The average value of the strength of two samples for each curing period is the split tensile strength of the sample.

The CBR tests were conducted on the optimum mixes obtained from unconfined compressive strength for each combination. The sample for conducting the CBR tests was prepared according to [59]. The surcharge was placed on the sample and soaking of the sample was done for a period of 4 days. The sample was removed from the water after 4 days prior to 15 minutes before conducting the test. The testing was conducted in a CBR testing machine and the CBR value (load/standard load) was a maximum of two values obtained for 2.5 and 5 mm penetrations.

Results and Discussion

Unconfined compressive strength. Influence of adding lime, fly ash and C&D waste individually on UCS of soil

The curves of unconfined compressive strength (UCS) versus the curing period (Fig. 3) reveal that the addition of different contents of admixtures such as fly ash, lime, and C&D waste increase the UCS value of the clay. The maximum increment in UCS value is observed upon the addition of optimum content (4 %) of lime, which is attributed to the chemical reaction among soil and lime particles.

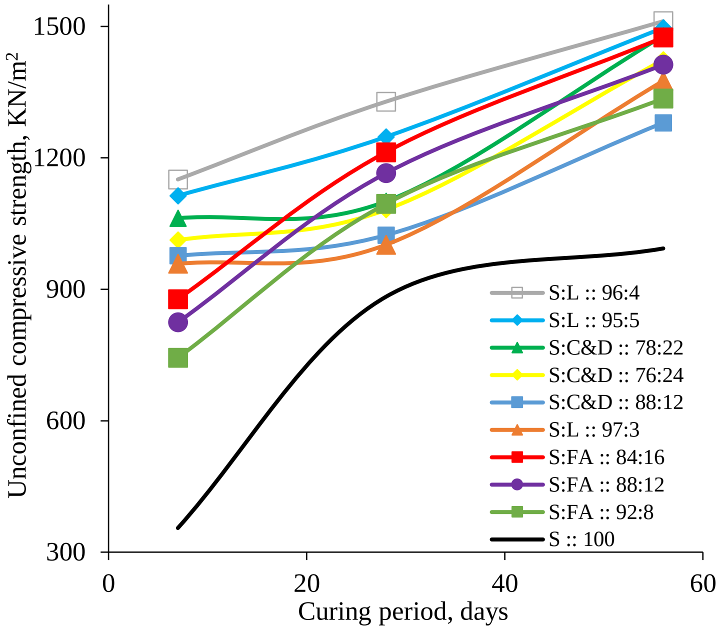

Fig. 3. Influence of addition of additives on UCS of soil with curing period

With the curing time, an increase in UCS value is noticed irrespective of the additive and additive content. The 7 days unconfined compressive strength is more on the addition of lime followed by C&D waste and fly ash. The strength increment is more for 4 % lime compared to 3 and 5 % lime content. The optimum content of lime may be taken as 4 % since a higher content of lime leads to the existence of free lime which tends to decrease the strength. Similarly, the strength of 78 % soil + 22 % C&D waste is more compared to 76 % soil + 24 % C&D waste and 88 % soil + 12 % C&D waste. The optimum content of C&D waste may be taken as 22 % at which the contents of compounds present in it are sufficient to complete the reaction and form new compounds like calciobetafite. There is no appreciable enhancement in the UCS value of soil-fly ash composite for fly ash content of more than 12 %. Hence, based on the above results, the optimum content of lime, fly ash, and C&D waste for stabilization of soil may be taken as 4, 12, and 22 % respectively. The strength gains up to 28 days curing period is more for soil-lime admixture followed by soil-fly ash admixture and soil-C&D waste admixture which indicates that the pozzolanic reaction between soil and fly ash and soil-C&D waste is relatively slow. The 28-day UCS value of 78 % soil + 22 % C&D waste is nearly the equivalent as that of 92 %

soil + 8 % fly ash which indicates that C&D waste is an effective stabilization material. Initially, there is less increase in the UCS value of soil on the addition of optimum C&D waste content (up to 28 days) but increases after 56 days and is comparable with the strength value obtained upon the addition of optimum lime content. This is mainly attributed to the slow pozzolanic reaction among soil and C&D waste particles. The UCS value of soil admixed with fly ash content (16 %) increases with the curing period and is comparable with that achieved upon adding the optimum lime content after 56 days curing period. Though strength is higher for 16 % fly ash content than that for 12% content its maximum dry density is less and hence 12 % fly ash content may be taken as the optimum. This increment in strength value on adding fly ash is attributed to the pozzolanic reaction among the particles of soil and admixtures. Thus, it can be observed that when the optimum content of the admixtures – lime or C&D waste or fly ash is added; the unconfined compressive strength achieved is comparable after 56 day curing period.

The X-ray diffraction (XRD) pattern of soil (Fig. 4(a)) reveals the existence of montmorillonite, quartz, and muscovite. The presence of montmorillonite indicates that the clay is very sensitive when it comes in contact with water and has high swelling properties.

The cause of improvement in the UCS value of soil on adding lime is due to the formation of new compounds like calcite, which was observed in the X-ray diffraction pattern presented in Fig. 4(b). The further increase in the UCS value of soil on adding fly ash is attributed to the formation of new compounds like mullite observed in the X-ray diffraction pattern Fig. 4(c).

On adding C&D waste to the soil, the formation of new compounds like calciobetafite was observed in the X-ray diffraction pattern presented in Fig. 4(d), which lead to an increase in the value of unconfined strength.

The difference between the 56 days of unconfined compressive strengths of the optimum soil-lime, soil-fly ash, and soil-C&D waste mixes is negligible. This indicates that all three additives are good stabilizers when long-term strength is a governing criterion. However, since lime is a costly material, it should be used only when short-term strength is the governing criterion. Fly ash is a waste material affecting the environment adversely but utilized for various purposes already in enormous quantities. The stabilization of soil requires less quantity (12 %) of fly ash compared with C&D waste, making it as the second-best alternative. The generation of C&D waste is increasing tremendously, whereas its utilization for construction purposes is very less presently. Hence, the utilization of large quantities (22 % as compared to 12 % fly ash) of C&D waste in soil stabilization will solve the problem of its disposal. Thus, C&D waste can also be selected as a good stabilizer comparable to other materials, taking into account its strength as well as economical and environmental considerations.

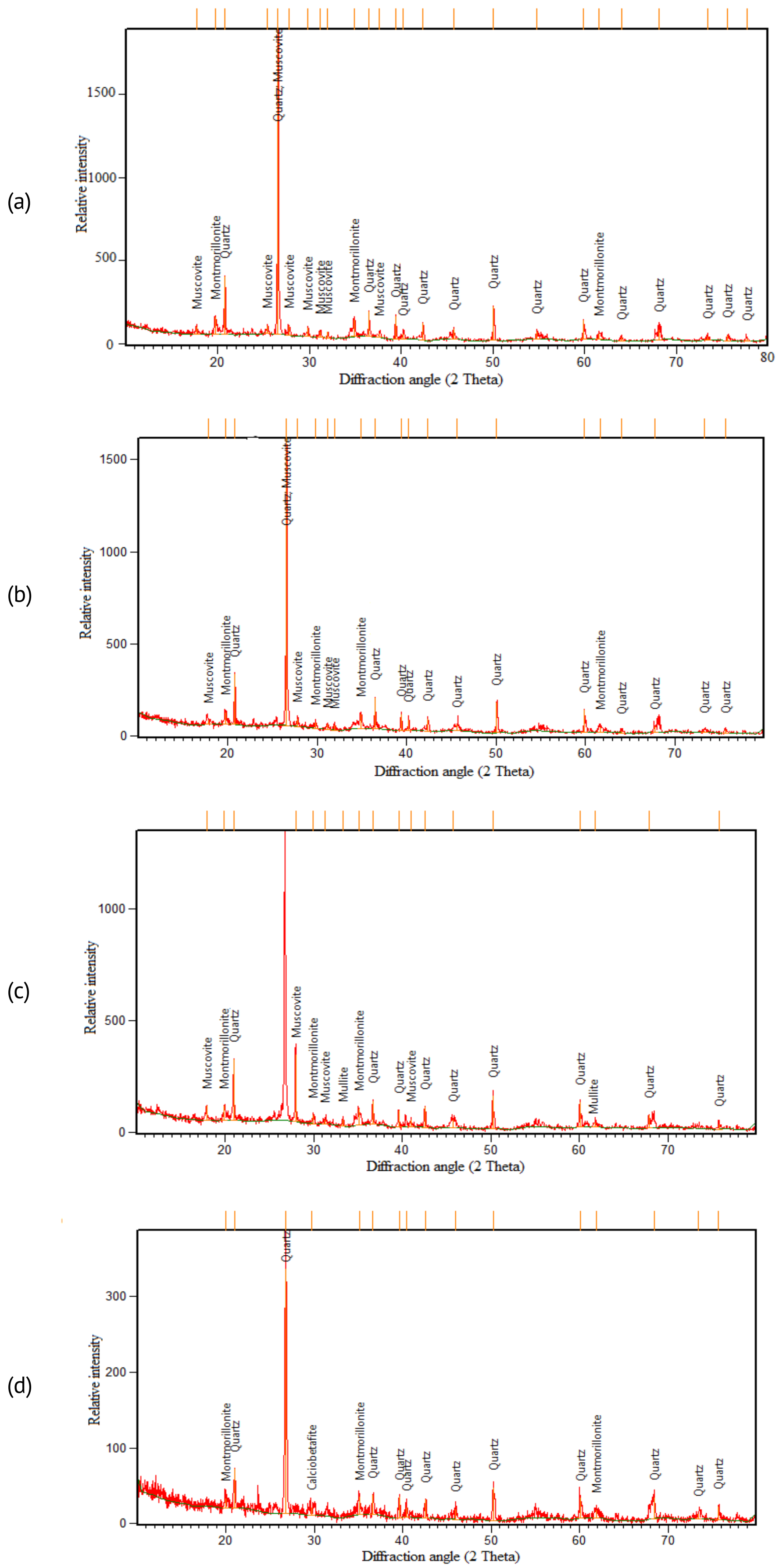

Fig. 4. XRD graph of soil (a), soil + lime (b), soil + fly ash (c), soil + C&D waste (d)

Influence of addition of fly ash and lime on UCS of soil

UCS tests were carried out on the optimum mixes soil-fly ash mix (obtained from UCS tests) with adding different percentages of lime obtained on the basis of unconfined compressive strength of soil-fly ash mixes and the curves between UCS value and curing period (Fig. 5) reveal the influence of lime on UCS value of soil-fly ash mix. The addition of lime increases the UCS of the mix, but the increase is less.

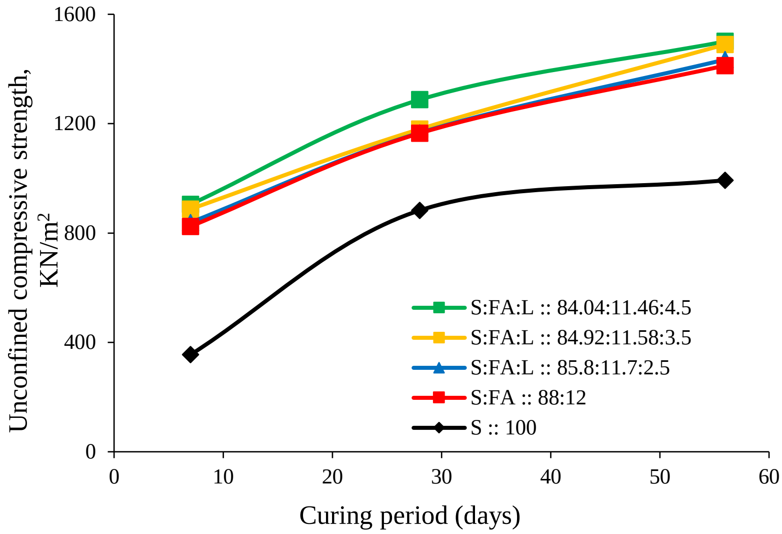

Fig. 5. UCS of soil, soil-fly ash mix, and soil-fly ash-lime mixes with curing period

The UCS value is more in the case of 84.04% soil + 11.46% fly ash + 4.5% lime, hence, this mix may be chosen as the optimum stabilized mix. The increase in strength is mainly because of the reduced rate of reaction among lime and soil-fly ash mix, since most of the pozzolanic reaction occurred with fly ash. A little increase in the UCS value of soil + fly ash mix on adding lime may be attributed to the presence of new compounds like calcite, as observed in the X-ray diffraction pattern presented in Fig. 6.

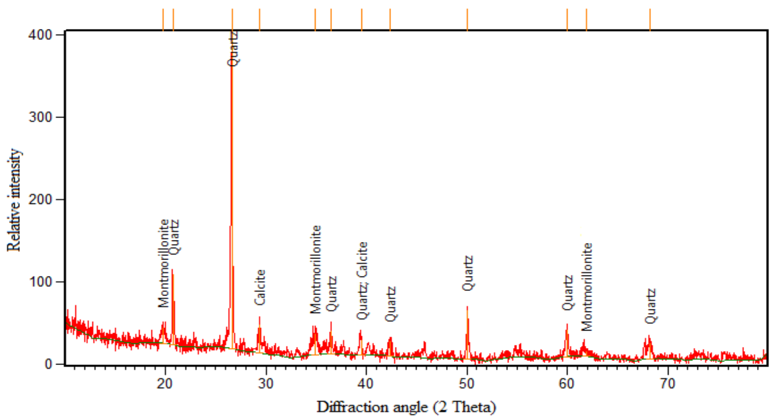

Fig. 6. XRD patterns of soil + fly ash + lime

Influence of addition of C&D waste and lime on UCS of soil

The optimum soil-C&D waste mix obtained based on the UCS test results was further stabilized by adding lime. The deviation of UCS value of soil-C&D waste mix with curing period corresponding to 0.49, 0.744, and 0.99 % lime contents is shown in Fig. 7, which indicates that 0.49 % lime content gives the maximum unconfined compressive strength value. Hence, 0.49 % lime content may be chosen as the optimum content for the stabilization of the soil-C&D waste mix. However, the addition of lime to the soil-C&D waste mix does not yield much increase in strength and lime may be added only if early strength is required. The little increase in strength is attributed to the reduced rate of reaction among lime and soil-C&D waste mix because the pozzolanic reaction already occurred with C&D waste. The addition of lime to the soil-C&D waste mix is a better option compared to soil-fly ash mix, which requires more lime content.

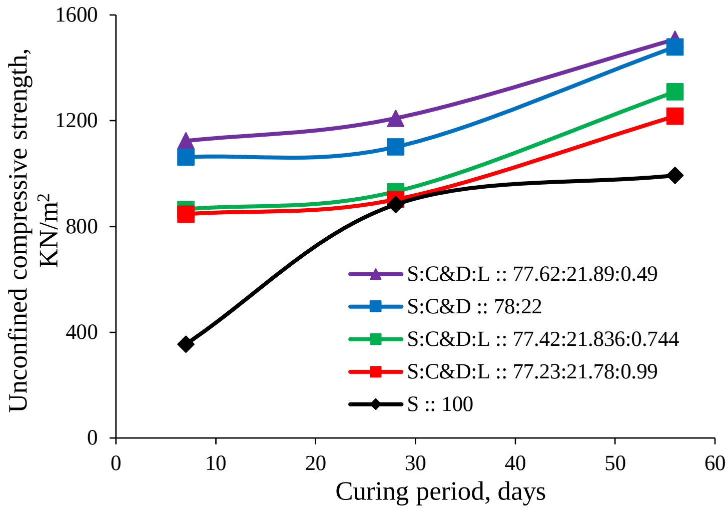

Fig. 7. UCS of soil, soil-C&D waste mix and soil-C&D waste-lime mixes with curing period

The X-ray diffraction pattern presented in Fig. 8 shows the presence of a small quantity of calcite, which causes less increase in unconfined compressive strength of soil + fly ash mixture on adding lime.

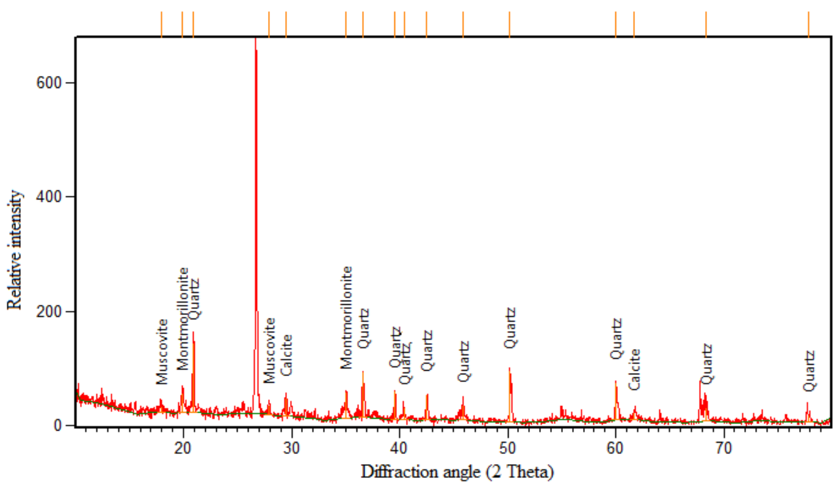

Fig. 8. XRD patterns of soil + C&D waste + lime

Influence of addition of fly ash and C&D waste on UCS of soil

The graph amongst UCS value and curing period presented in (Fig. 9) describes the influence of mixing of two waste materials fly ash and C&D waste. Adding both the materials fly ash and C&D waste together to the soil increases the unconfined compressive strength, which is more as compared to adding fly ash and C&D waste individually. The 7 days unconfined compressive strength is more for soil-C&D waste mix in comparison to soil-fly ash-C&D waste mix whereas 28 and 56 days UCS value is more for optimum soil-fly ash-C&D waste mix compared to soil-fly ash mix and soil-C&D waste mix and is mainly attributed to the higher pozzolanic reaction occurring among soil, fly ash and C&D waste. The UCS value of 65 % soil + 17 % fly ash + 18 % C&D waste is more compared to 64% soil + 18% fly ash + 18% C&D waste mix and 66% soil + 17% fly ash + 17 % C&D waste, and, therefore, 65 % soil + 17 % fly ash + 18 % C&D waste mix is finalized as an optimum mix to be used for soil stabilization. The stabilization of soil using both fly ash and C&D waste is an eco-friendly option because the dumping problem of both materials can be solved and the amount of fly ash (17 %) required in this mix is more than that of the amount of fly ash (12 %) required in soil stabilization using fly ash alone. Upon comparison of unconfined compressive strengths of optimum mixes of soil-fly ash-lime, soil-C&D waste-lime, and soil-fly ash-C&D waste (Figs. 5,7,9), it may be observed that the strength achieved after 56 days curing period is nearly the same. The quantity of the admixtures used in the above combinations is 12 % fly ash + 4.5 % lime, 21.89 % C&D waste + 0.49 % lime, and 17 % fly ash + 18 % C&D waste respectively. This indicates that the optimum combination of soil-fly ash-C&D waste mix involves the utilization of 35 % of waste materials without the addition of lime (which is costly). Thus, the soil-fly ash-C&D waste mix is economical and helps in minimizing the adverse effects of the waste materials on the environment besides giving a solution to dumping problems of waste materials.

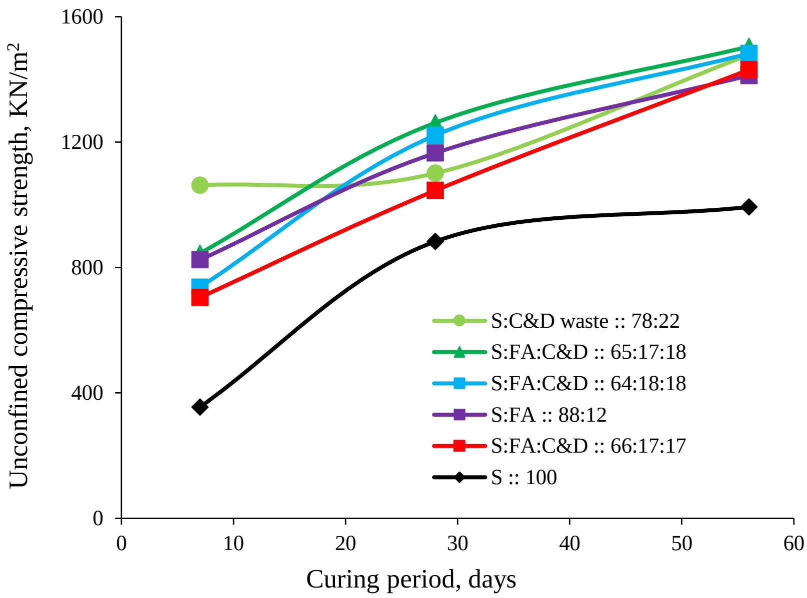

Fig. 9. Variation in UCS of soil and soil-fly ash-C&D waste mixes with curing period

The addition of waste materials such as fly ash and C&D waste to soil results in the formation of new compounds like mullite as observed in the X-ray diffraction pattern (Fig. 10), which increases the UCS value of soil.

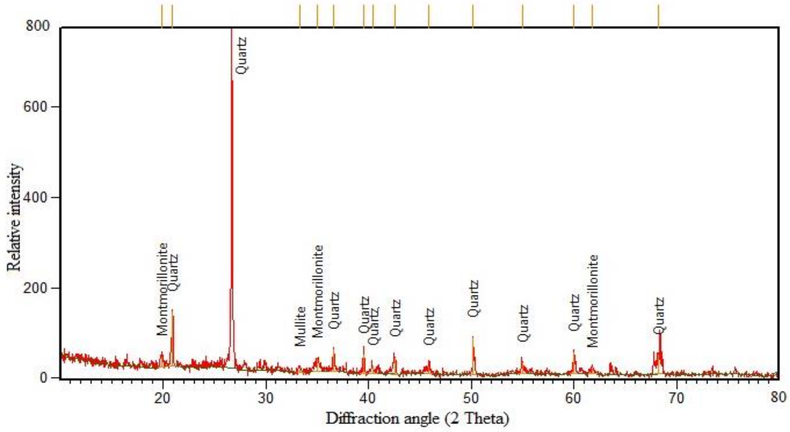

Fig. 10. XRD patterns of soil + fly ash + CDW

Influence of addition of fly ash, C&D waste and lime on UCS of soil

The lime was added to the optimum soil-fly ash-C&D waste mix in percentages of 0.99, 1.96, and 2.91 to explore its influence on UCS value. The curves between UCS value and curing period (Fig. 11) indicate that the unconfined compressive strength does not change appreciably up to 0.99 % lime content, but there is a reduction in strength for higher lime content (1.96 and 2.91 %). Thus, the addition of lime hardly shows any increase in strength with, however, 0.99 % lime content may be considered the optimum for the stabilization of soil-fly ash-C&D waste mix. The reduction in UCS value on the addition of lime occurs because of the presence of unreacted lime which creates a loose structure and causes sudden failure of the specimen as can be observed from the sudden drop in the unconfined compressive stress – axial strain curve shown in Fig. 12.

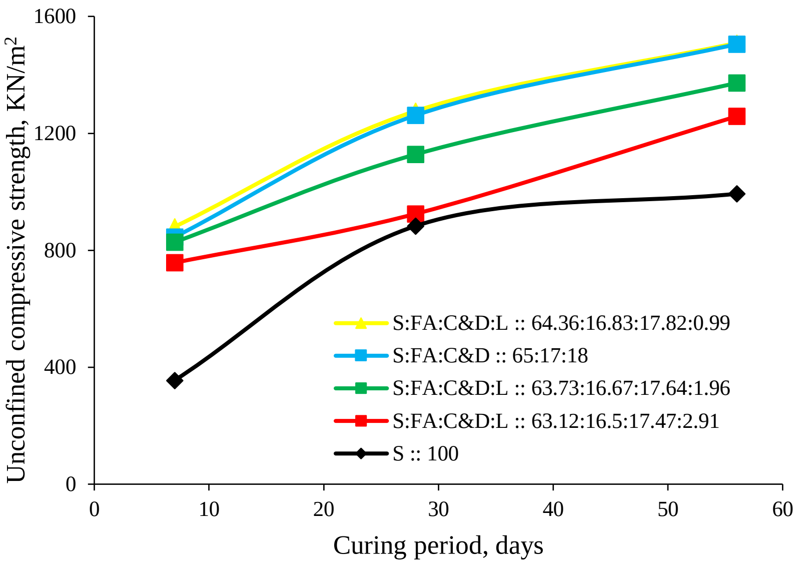

Fig. 11.-Variation in UCS of soil, soil-fly ash-C&D waste mix and soil-fly ash-C&D waste-lime mixes with curing period

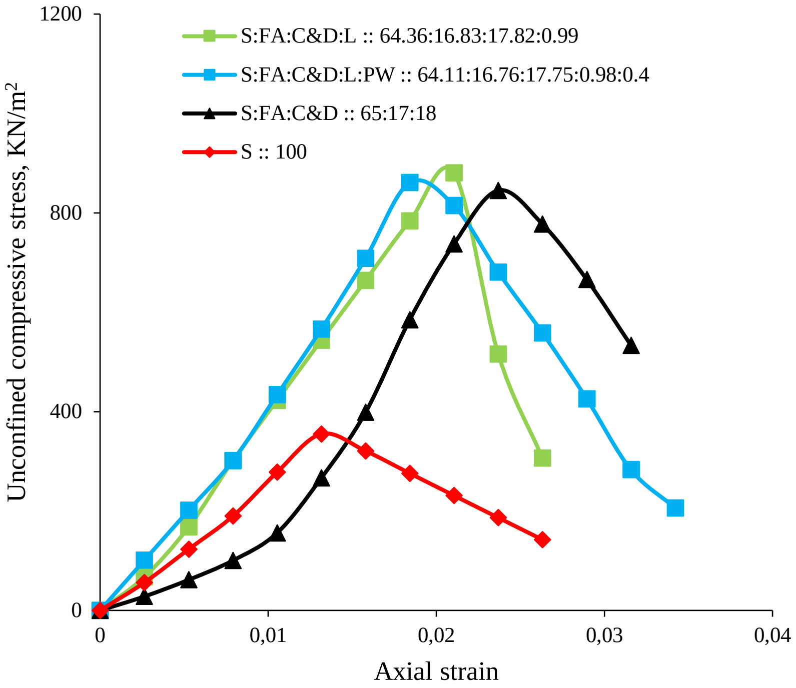

Fig. 12. Stress-strain curves of soil, soil-fly ash-C&D waste mix, soil-fly ash-C&D waste lime mix and soil-fly ash-C&D waste-lime-plastic waste mix

The lesser enhancement in UCS value can be accredited to the presence of minerals like calcite (Fig. 13) as observed from the X-ray diffraction pattern of soil + fly ash + C&D waste + lime.

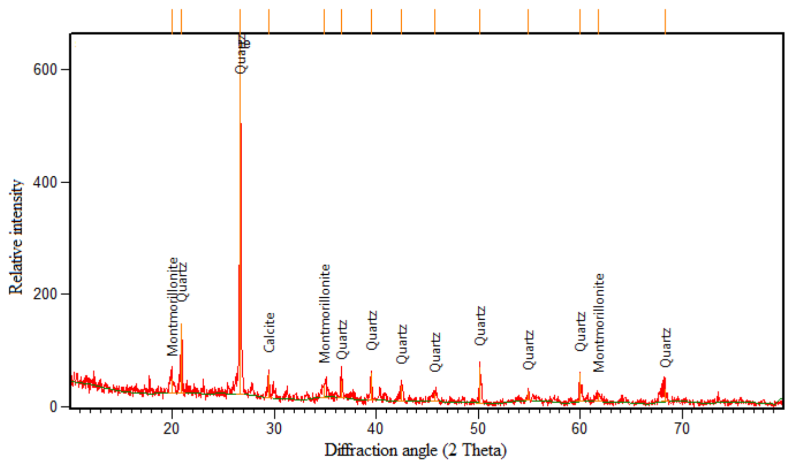

Fig. 13. X-Ray Diffraction patterns of soil + fly ash + C&D waste + lime

Influence of addition of fly ash, C&D waste, lime and plastic waste on UCS of soil

The effect of the addition of plastic waste to soil-fly ash-C&D waste-lime mix on UCS value and curing period is shown in Fig. 14. The addition of plastic waste (PW) decreases the UCS value of the mix. The rate of decrease is less in the case of the addition of 0.4 % plastic waste, followed by 0.6 and 0.2 % plastic waste contents. Hence, 0.4 % plastic waste content may be chosen as the optimum content for soil stabilization. The decrease in the UCS is due to the reduction in MDD, which may be due to a little loosening of the mix with the addition of plastic waste. The curves of unconfined compressive strength versus the curing period for soil-fly ash-C&D waste-lime-plastic waste mixes reveal that there is a linear increase in strength with the curing period. Further, the addition of plastic waste changes the material behavior from brittle to ductile, as can be observed from the unconfined compressive stress−axial strain curves (Fig. 12). A similar trend indicating the change in stress-strain behavior from brittle to ductile upon the addition of fiber has been reported in [45].

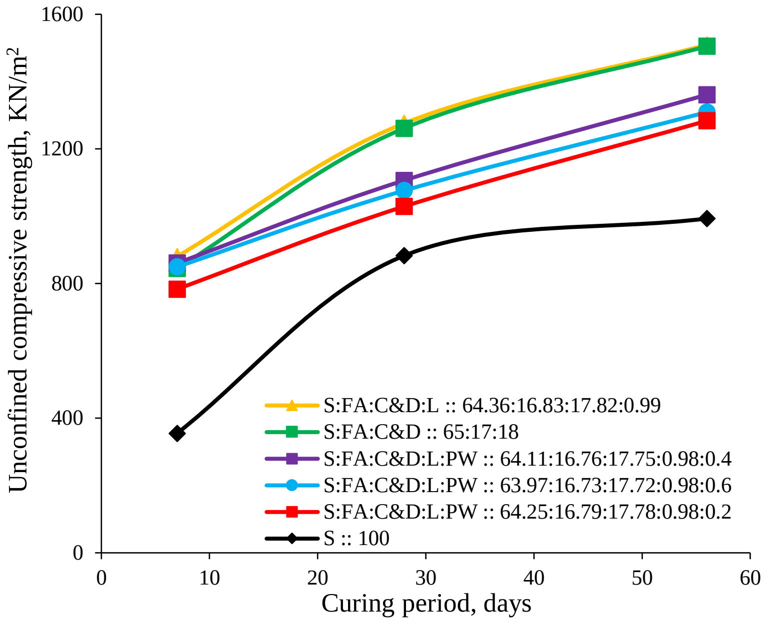

Fig. 14. Variation in UCS of soil, soil- fly ash-C&D waste mix, soil-fly ash-C&D waste-lime mix and soil-fly ash-C&D waste-lime-plastic waste mixes with curing period

Thus, based on the unconfined compressive strength values, it can be established that C&D waste is a better stabilizer in comparison to fly ash and lime when added individually to the soil. When two admixtures are added together to the soil, the best material combination is soil-fly ash-C&D waste followed by soil-C&D waste-lime and soil-fly ash-lime. The addition of lime to the soil-fly ash-C&D waste mix causes hardly any increment in UCS value. The addition of plastic waste to soil-fly ash-C&D waste-lime mix though reduces the unconfined compressive strength but deviates the composition of the mixture from brittle to ductile.

Split tensile strength

As per [60], the design of pavement is achieved on the basis of UCS and CBR values of the subgrade. Further, the tensile stresses are generated in the pavement due to variations in temperature and vehicle movement. In order to make the pavement free from tension cracks, the split tensile strength of sub-grade material should be known and should be included in the design of pavements as per [60]; this is the reason for including split tensile strength tests in present research work.

Influence of addition of lime, fly ash and C&D waste individually on STS of soil

The split tensile strength tests were performed on soil and various soil additives after a curing period of 7, 28, and 56 days. The influence of lime, fly ash, and C&D waste on the STS of soil at various curing periods is shown in Fig. 15. The curves reveal that STS increases with the curing period and the addition of different additives. The addition of lime increases STS value more due to the chemical reaction between the soil and lime particles, which is further followed by C&D waste and fly ash. The increase in strength on adding fly ash and C&D waste is due to the pozzolanic reaction between the particles of soil and admixtures. The split tensile strength increases with the curing period, irrespective of the type of additive and additive content. Based on the results, the strength of the soil-C&D waste mix is comparable with that of the soil-lime mix, and hence C&D waste is an effective stabilizing material.

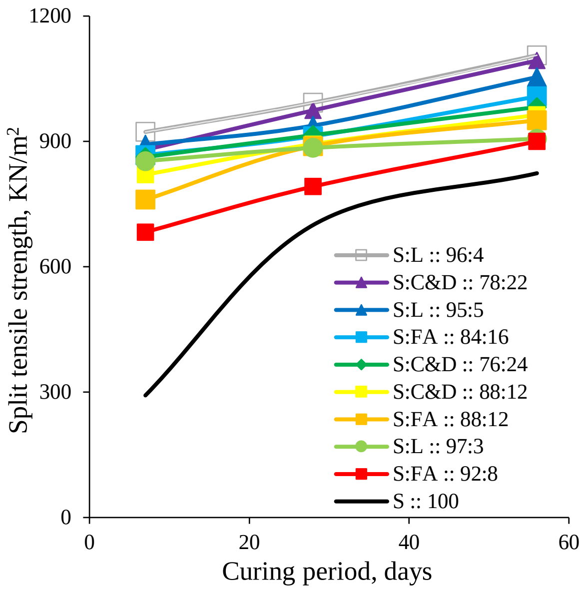

Fig. 15. Effect of addition of additives on STS of soil with curing period

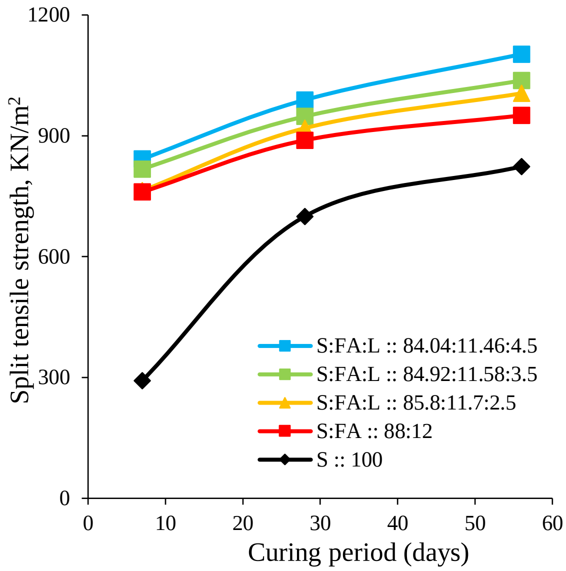

Fig. 16. STS of soil, soil-fly ash mix and soil-fly ash-lime mixes with curing period

Influence of addition of fly ash and lime on STS of soil

Lime is added in percentages of 2.5, 3.5, and 4.5 %, respectively on the optimum soil-fly ash mix and STS tests were performed on these mixes. The influence of adding lime on the split tensile strength of the soil-fly ash mix is presented in Fig. 16. The split tensile strength of soil-fly ash-lime mix increases with an increase in lime content and curing period. This increase is attributed to the chemical reaction between lime and soil-fly ash particles. The split tensile strength is more on adding 4.5 % lime content, hence, 4.5 % lime content may be taken as the optimum value. Although the split tensile strength increases significantly, however, lime is a costly material.

Influence of addition of C&D waste and lime on STS of soil

The split tensile strength tests were conducted on optimum soil-C&D waste mix stabilized with 0.49%, 0.744%, and 0.99% lime contents. The split tensile strength results are plotted as split tensile strength (STS) versus the curing period (Fig. 17) showing the consequence of the addition of lime to the soil-C&D waste mix. Figure 17 reveals that there is hardly any enhancement in STS of soil-C&D waste mix with the addition of 0.49 % lime content, whereas higher lime content reduces the split tensile strength of the mix. The improvement in strength with the addition of lime is very limited, hence, it is better to avoid adding lime to the soil-C&D waste mix.

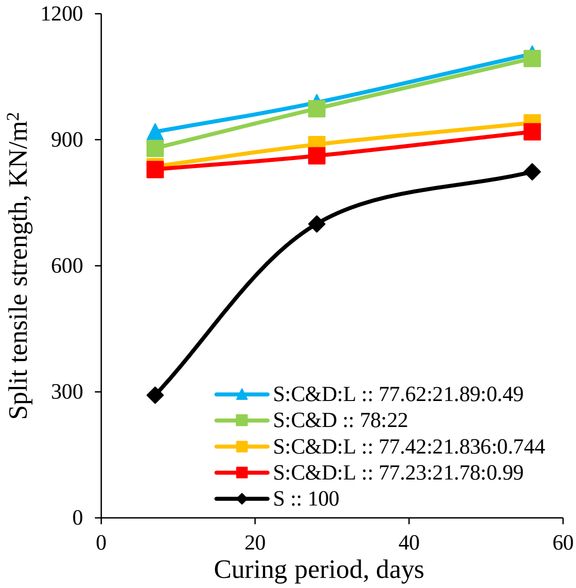

Fig. 17. STS of soil, soil-C&D waste mix and soil-C&D waste-lime mixes with curing period

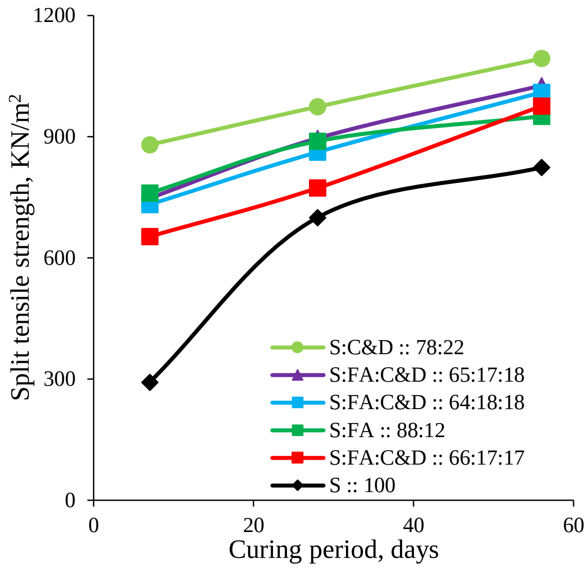

Fig. 18. Variation in STS of soil and soil-fly ash-C&D waste mixes with curing period

Influence of addition of fly ash and C&D waste on STS of soil

The plot of the split tensile strength (STS) versus curing period (Fig. 18) shows the effect of the addition of two pozzolanic materials viz; fly ash and C&D waste to poor soil. The split tensile strength of the soil-fly ash-C&D waste mix is nearly the same as that of the soil-fly ash mix, but is less than that of the soil-C&D waste mix. The reduction in strength of soil-fly ash-C&D waste mixes compared to the soil-C&D waste mix is due to their less maximum dry density. The maximum split tensile strength is observed for 65% soil + 17% fly ash + 18% C&D waste mix compared to that of 64% soil + 18% fly ash + 18% C&D waste and 66% soil + 17% fly ash + 17% C&D waste mixes. There is no appreciable variation in split tensile strength of soil + fly ash mix on adding C&D waste, rather it is somewhat less for some combinations. However, more quantity of waste materials (34%-36% fly ash + C&D waste compared with 12% fly ash only) can be utilized, thus reducing detrimental effects on the environment.

Influence of addition of fly ash, C&D waste and lime on STS of soil

The effect of the addition of 0.99, 1.96, and 2.91 % lime content on the STS value of optimum soil-fly ash-C&D waste mix is shown in Fig. 19, which reveals that higher STS is observed for 0.99 % lime content and addition of more lime decreases the split tensile strength drastically which may be due to free the occurrence of unreacted lime. The increase in strength with the addition of lime is very, and it being a costly material should be used only when it is important from other design considerations.

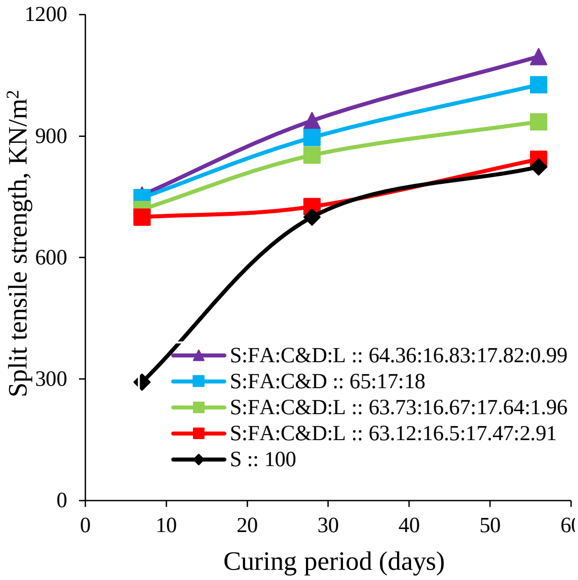

Fig. 19. Variation in STS of soil, soil-fly ash-C&D waste mix and soil-fly ash-C&D waste-lime mixes with curing period

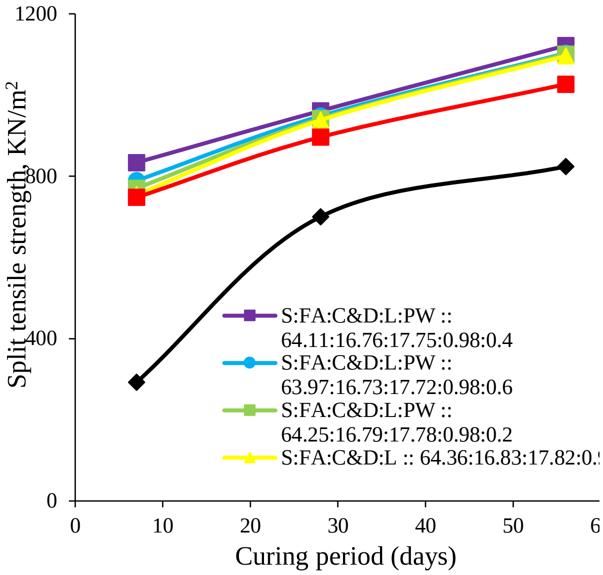

Fig. 20. Variation in STS of soil, soil-fly ash-C&D waste mix, soil-fly ash-C&D waste-lime mix and soil-fly ash-C&D waste-lime-plastic waste mixes with curing period

Effect of addition of fly ash, C&D waste, lime and plastic waste on STS of soil

Plastic waste is added to the soil-fly ash-C&D waste-lime mix in percentages of 0.2, 0.4, and 0.6 to study its effect on split tensile strength of the mix. The STS versus curing period plot (Fig. 20) illustrates the effect of the addition of plastic waste to soil-fly ash-C&D waste mix. The slight increase in strength is pronounced by the addition of 0.4 % plastic waste content and is more as compared to 0.6 % plastic waste and 0.2 % plastic waste. Thus, 0.4 % plastic waste can be selected as the optimum content for the stabilization of soil-fly ash-C&D waste-lime mix. The reason for the enhancement in STS value may be due to increase in interfacial friction, which may be due to the effective contact area between plastic and the mixed material. Further, the reduction in the split tensile strength beyond 0.4 % plastic waste may be because plastic-to-plastic interaction dominates the plastic-to-particle interaction, making it the weakest failure plane to fail, which is in agreement with the results reported in [45].

It is observed on the basis of the above results that UCS value and STS value increase with curing time. The 360 days STS value is necessary for the design of pavement for high-intensity traffic. The correlation suggested between $q_{t360days}$ and $q_{t28days}$ [7], which is represented by the equation:

$$\frac{q_{t28days}}{q_{t360days}} = 0.60. \quad (1)$$

From the above equation, we can find out the 360 days split tensile strength of the mix, which can be used in the design of pavements. For the optimum soil-fly ash-C&D waste-lime-plastic waste mix, the 360 days split tensile strength is: $q_{t360days} = q_{t28days}/0.6$ = = 960.9 / 0.6 = 1601.5 KN/m^2 = 1.6015 MPa, which is more than the required strength.

California bearing ratio

On the basis of optimum mixes obtained from UCS tests, the soaked CBR tests were piloted. The effect of the addition of various admixtures on the soaked CBR value of soil is shown in Fig. 21. The soaked CBR value of soil is 1.6% which with the addition of optimum content (12 %) of fly ash increases to 3.2 %. The soaked CBR value of 96 % soil + 4% lime is 12.7 % which is 8 times that of the CBR value of soil. The addition of 22 % C&D waste increases the soaked CBR value to 4.4% which is two and half times that of soil.

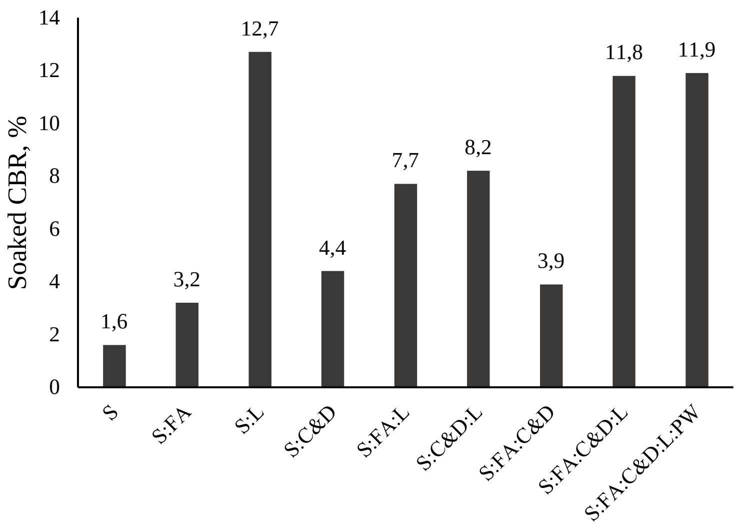

Fig. 21. Variation of soaked CBR values on addition of different admixtures

The soaked CBR value is 7.7 for 84.04 % soil + 11.46 % fly ash + 4.5 % lime, which can be used as a sub-grade material for pavement as per [60]. The soaked CBR value of 77.62 % soil + 21.89 % C&D waste + 0.49 % lime is 8.2 which is higher than the value of CBR obtained for the soil-fly ash-lime mix. The addition of fly ash and C&D waste together increases the soaked CBR value to 3.9 % which is very less compared to soil-fly ash-lime mix and soil-C&D waste-lime mix. The soaked CBR value of 64.36 % soil + 16.83 % fly ash + 17.82 % C&D waste + 0.99 % lime is 11.8 which is very close to that of 96 % soil + 4 % lime. The soaked CBR value of 64.11 % soil + 16.76 % fly ash + 17.75 % C&D waste + 0.98 % lime + 0.4 % plastic waste is 11.9, which is nearly the same as that of the soil-fly ash-C&D waste-lime mix. The above results reveal that the soil alone has a very low CBR value, and it requires stabilization using different additives. When stabilized by using two pozzolanic materials i.e. fly ash and C&D waste individually or in combination with each other, the CBR value increases, but the increase is not sufficient to make it suitable for use as a sub-grade material in road pavement (CBR > 6 is generally required). The increase in CBR value is not appreciable due to the absence of a binder in the mixes, as reported in [45]. The CBR value increases appreciably when lime is added to soil + fly ash and soil + C&D waste mixes making it suitable as a sub-grade material. However, for soil + C&D waste mix, the lime content required is only 0.49 % which is much less compared to that required for 4.5 % for soil + fly ash mix. Also, the CBR value for soil + C&D waste mix is higher than that of soil + fly ash mix and a larger quantity of C&D waste (21.89% compared to 12 % fly ash) is used for stabilization. Also, the class F fly ash (used in this research work) may contain harmful trace elements such as Pb, Cd, Ni, etc. as shown in [34]. Thus, the use of class F fly ash alone may pollute the groundwater and cause adverse effects on the environment but when class F fly ash is used with lime, the release of metals is prevented as reported in [35] due to its alkaline nature (pH of lime = 12); thus, preventing detrimental effects to health and environment. The CBR value of the soil-fly ash-C&D waste-lime mix is very close to the soil-lime mix thus, based on the results soil-fly ash-C&D waste-lime mix is best to mix compared to the soil-lime mix because the amount of lime required in the soil-fly ash-C&D waste-lime mix is less and also the waste materials such as fly ash and C&D waste which pose difficulty in their disposal can also be utilized in this mix. On adding plastic waste to soil-fly ash-C&D waste-lime mix, there is a negligible effect of CBR value, but it can be used along with the mix because it improved the tensile strength of the composite and its disposal problem can also be solved.

Pavement design

The effect of the addition of admixtures on pavement design can be explained in terms of the pavement thickness required. The design of pavement is achieved by considering traffic of 10 million standard axles and as per [60]. The effect of stabilization of soil with various admixtures is observed on the thickness of the pavement. It was observed from Fig. 22 that pavement thickness decreases with stabilization. The decrease in pavement thickness is more in the case of soil stabilized with 4 % lime.

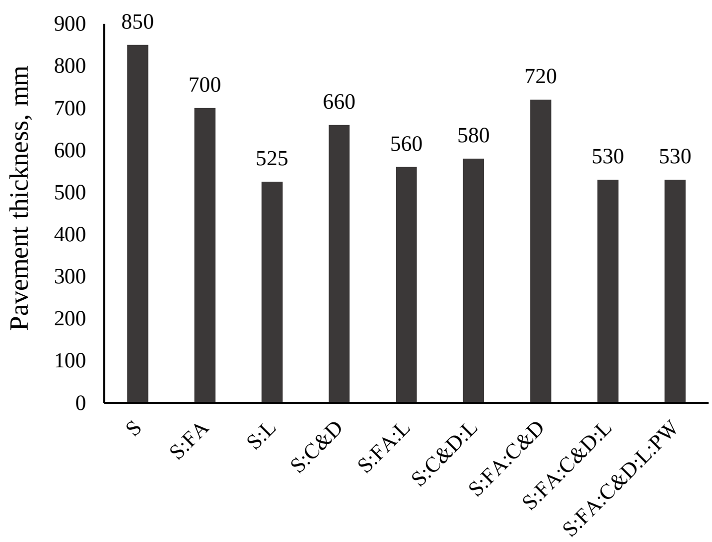

Fig. 22. Effect of addition of admixtures on pavement thickness

Similar pavement thickness can be observed for clay stabilized using fly ash, C&D waste & 0.99% lime content which is a cost-effective as well as eco-friendly mix since the disposal problem of fly ash and C&D waste can be solved. The effect of the addition of plastic waste on S+FA+C&D+L has a negligible effect on pavement thickness, but it increases the tension-carrying capacity of the sub-grade making it free from cracks. Thus, for sub-grade material, a combination of the soil-fly ash-C&D waste-lime-plastic waste mix can be effectively used.

Conclusions

Various tests were conducted in the laboratory to gain knowledge about the influence of the addition of fly ash, lime, C&D waste, and plastic waste on the clay and the following important conclusions were made:

1. A decrease in the value of maximum dry density is observed on the addition of various additives to the soil.
2. The unconfined compressive strength of the mix increases on adding various additives individually and in combination with each other, and it increases with curing period.
3. There is a little reduction in value of unconfined strength on adding plastic waste to soil mix.
4. With the curing period, the split tensile strength increases and also increases by adding different additives alone and in combination to each another.
5. The optimum mix is selected based on 7 days of unconfined compressive strength and split tensile strength of the mixes.
6. Considering the California bearing ratio, economy, and environment; the soil-fly ash-C&D waste-lime mix is selected as the optimum mix to be used as a sub-grade material. When the disposal of plastic is a problem, soil-fly ash-C&D waste-lime-plastic waste can be selected as sub-grade material.
7. When there is option of choosing fly ash or C&D waste, C&D waste can be selected as stabilizer for soil because it does not contain any harmful trace elements whereas fly ash contains harmful trace elements which are dangerous to the environment.
8. The use of fly ash alone may pollute the groundwater, whereas use of lime along with fly ash prevents the release of harmful metals from fly ash making it eco-friendly.

The results of the present study are applicable to improving the behaviour of poor clay soil ensuring the load-bearing capacity and quality of soil in preparation for road construction projects.

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