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Sustainable Utilization of Waste Foundry Sand and Sodium Chloride in Soil Stabilization

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Abstract

The expansion and contraction properties of black cotton soil make it a challenging task to construct structures on it. Hence, modifying its expansion and contraction behavior is imperative to make black cotton soil appropriate for construction purposes. This study aims to assess the geo-technical properties of black cotton soil through laboratory testing, incorporating waste foundry sand (WFS) and sodium chloride (NaCl) to utilize the combination as sub-grade material. Differential free swell, consistency limits, the standard Proctor test, and California bearing ratio (CBR) tests are conducted with varying amounts of both materials. The laboratory testing reveals that the addition of the appropriate amount of waste foundry sand, sodium chloride, or both, improve the geo-technical properties of black cotton soil (BCS). Furthermore, using the CBR values obtained, the thickness of flexible pavement is designed with the IITPAVE software and evaluated against the IRC: 37-2018 recommendations. The software analysis demonstrates a reduction in pavement thickness for varying levels of commercial vehicles per day such as 1000, 2000, and 5000 CVPD across all combinations. This mixture not only addresses the issues related to black cotton soil but also provides an economical solution for soil stabilization and proves to be sustainable as it involves the utilization of waste materials such as waste foundry sand.

1. Introduction

Black cotton soil, a type of expansive soil, can be found in the North-eastern part of Nigeria, Cameroon, the Lake Chad Basin, Sudan, Ethiopia, Kenya, and South Zimbabwe [1, 2]. Additionally, this type of soil can be found in India, Australia, the south-western region of the United States of America, South Africa, and Israel. It is prevalent in semi-arid regions of the tropics where the rate of annual evaporation surpasses that of precipitation [3,4, 5]. Black cotton soil is primarily composed of clay, lime, iron, carbonate, magnesium, and trace amounts of organic matter, nitrogen, phosphorus, and other elements. It possesses poor load-bearing capacity, high moisture absorption ability, low shear strength, and a high plasticity value [6, 7]. The use of black cotton soil in construction has always been challenging, as it is not deemed appropriate for constructing buildings or roads. Consequently, numerous studies have been conducted to explore methods of enhancing the sub-grade by stabilizing it and enhancing the soil's engineering characteristics [8]. Black cotton soil (BCS) is susceptible to swelling and shrinkage because of its tendency to react with moisture. The resulting expansion and contraction of the soil can cause damage to the structures built on it [9,10, 30]. Construction on soils that experience differential settlement is typically avoided due to potential issues. However, when construction is unavoidable, these soils must be stabilized beforehand. There are several traditional techniques that can be used to improve the geotechnical characteristics of poor soils including physical and chemical stabilization, soil reinforcement, sand replacement methods, and sand cushioning methods. However, these methods can be expensive. As a result, the researchers are continuously searching for more cost-effective alternatives to improve soil properties. One such technique, which has been used for the past two

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decades, is soil stabilization using waste materials. This method involves using various waste materials such as industrial, construction and demolition, and agricultural wastes [9,11 & 12].

Waste Foundry Sand (WFS) refers to the non-hazardous material that is acquired from the metal casting industries, both ferrous and non-ferrous. The sands are used repeatedly in the casting process until they deteriorate to a point where they can no longer be reused. At this stage, the used sand is considered a by-product and is replaced with fresh sand to continue the cycle [13]. The chemical composition of WFS varies depending on the source of the sand and the type of metal or non-metal used in the casting process [14]. Typically, WFS has a high silica content, which is the main constituent of the sand. Additionally, it may contain small amounts of binder materials, clay, and trace elements such as calcium, iron, and aluminium [15, 16]. Due to its abundance of silica, WFS provides strength and stability to construction materials, and its low compressibility and permeability make it suitable for soil stabilization efforts. Furthermore, incorporating WFS into concrete and asphalt can increase their durability and strength [10, 17, 18 & 19].

Sodium chloride is a type of salt that can be incorporated into the ground to enhance its composition and workability [20]. By combining the soil with sodium chloride, its plasticity is enhanced and its compressibility is reduced, leading to an increase in the soil's load-bearing capacity and thus, making it less susceptible to distortion [21]. The addition of sodium chloride affects the properties of soil, resulting in an increase in MDD and a decrease in optimum moisture content up to a 2.5% increment. Both the liquid limit and plastic limit reduce, whereas the CBR value (unsoaked) increases to 98% compared to virgin soil at 2.5% dosage. Additionally, the UCS sample results show that after 24-hour curing, there is a 50% increase compared to virgin soil, with a further 67% increase following 7-day curing [22]. Previous studies have revealed that incorporating chemical admixtures like sodium chloride (NaCl), calcium chloride ($CaCl_2$), and sodium hydroxide (NaOH) into cement-stabilized clay soil can result in increased unconfined compressive strength (UCS) [23, 29].

Previous studies have shown that the incorporation of WFS or NaCl can enhance the strength of clayey soil. However, there is limited research on the effectiveness of WFS-NaCl mixtures. Therefore, the current study aims to investigate the potential of using WFS and NaCl both separately and in combination to improve the geotechnical characteristics of black cotton soil for sub-grade applications. Successful findings from this research work could pave the way for utilizing these waste materials in the construction of durable and cost-effective pavements, reducing reliance on traditional construction materials, minimizing land misuse for unregulated waste disposal, lowering road construction expenses, and protecting the environment from waste-related damage.

2. Materials

2.1. Soil

The black cotton soil utilized in the experiments was sourced from Chhindwara, Gwalior district, Madhya Pradesh. The soil was dried using natural sunlight, and the larger chunks were then crumpled to make it suitable for use. To prevent moisture from entering, the crushed soil was filled into air-tight bags. Wet sieve analysis and hydrometer analysis were used to determine the soil size particle distribution curve, which revealed that the soil had high plasticity and fell within the CH range (clay of high plasticity) conferring the Unified Soil Classification System (as shown in Figure 1). Table 1 presents the geotechnical properties of the black cotton soil used in this study.

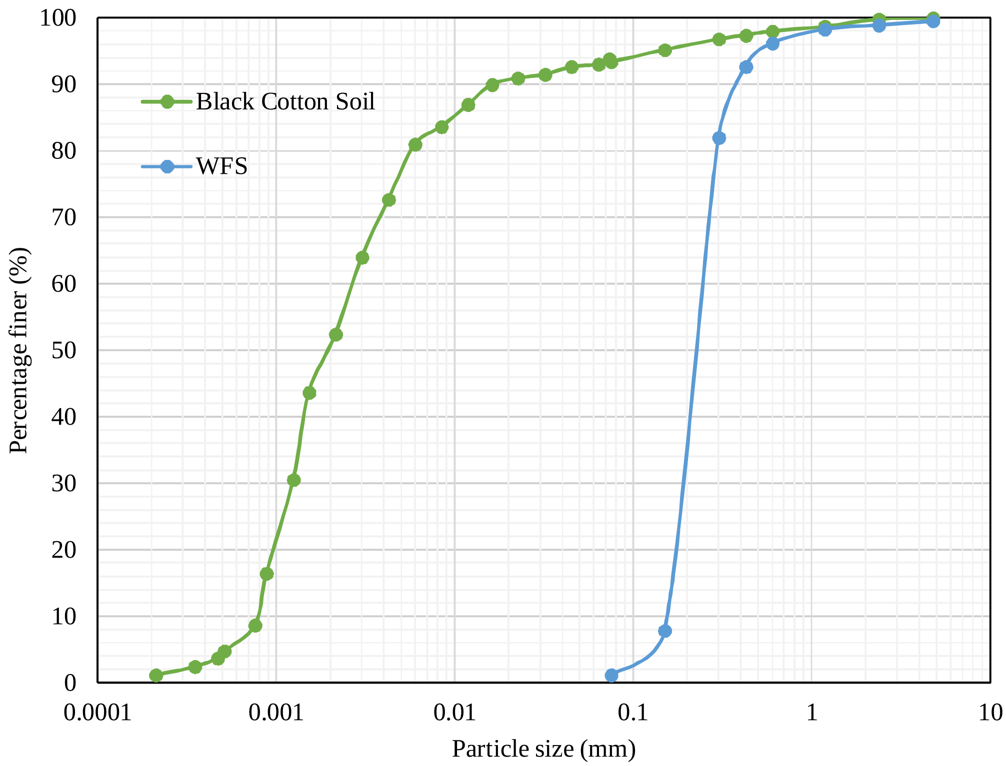

Figure 1. Grain size distribution of black cotton soil and WFS.

2.2. Waste foundry sand (WFS)

This research work utilized WFS procured from Shakti Industries located in Ludhiana, Punjab. Figure 1 illustrates the particle size distribution of WFS, which was utilized for laboratory testing at varying proportions of 7%, 14%, 21%, and 28%. It is considered poorly graded sand with C_u and C_c of 1.5 and 0.94, respectively (Table 1). The physical properties of this WFS are presented in Table 1.

2.3. Sodium chloride (NaCl)

Sodium chloride is a white crystalline substance that has deliquescent and hygroscopic properties. It may be used to reduce or prevent frost heave in soil by lowering the vapor pressure of water, as well as prevent the formation of shrinkage cracks through its dust palliative capabilities. NaCl was purchased from a store in Kharar, Punjab, and kept in a dry environment to prevent any moisture from entering it. Different amounts of sodium chloride were added in its dry form at various ratios, such as 2%, 4%, 6%, and 8%. The characteristics of NaCl are detailed in Table 1.

Table 1. Properties of black cotton soil, waste foundry sand, and sodium chloride.

Properties	Black cotton soil	Waste foundry sand	Sodium chloride
Type	CH	SP	NaCl
Physical appearance	Greyish-black	Black	White
Liquid Limit (LL) (%)	70	-	-
Plastic Limit (PL) (%)	20.80	-	-
Plasticity Index (I_p) (%)	39.43	-	-
Specific Gravity (g/cc)	2.68	2.44	2.01
DFS (%)	50%	-	-
OMC (%)	20	15	-
MDD, g/cm^3	1.56	1.42	-
Coefficient of uniformity (C_u)	-	1.5	-
Coefficient of curvature (C_c)	-	0.94	-

3. Methodology

The laboratory experiments followed the guidelines outlined in the ASTM and IS codes, with a particular focus on studying the physical properties of black cotton soil and its mixtures with Waste Foundry Sand (WFS) and sodium chloride (NaCl). The test included measuring the consistency limits and Differential Free Swell (DFS) index, which are the critical parameters for black soil. The study examined numerous combinations of soil and additives to obtain their Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Moreover, the California Bearing Ratio (CBR) was assessed for the soil alone and in conjunction with other additives, with adherence to the relevant codes to ensure precise and standardized testing procedures. Table 2 tabulates the ratios of different components that have been established through prior research evaluations.

4. Results

4.1. Differential Free Swell

The DFS value of black soil was determined to be 50%. As the amount of WFS and NaCl increased, there was a gradual decrease in the DFS value. When WFS was incorporated up to 21% into the black cotton soil, the DFS value reached zero (Figure 2). Further addition of WFS to the soil did not alter the DFS value, and it continued to be zero. The optimal WFS content for stabilizing black cotton soil was determined to be 21%. The reduction in DFS value upon adding WFS may be attributed to the enhanced proportion of coarser particles in the soil, which decreases its surface activity [24]. Adding 6% NaCl to black cotton soil also lowered the DFS value to zero; however, the addition of a further amount of NaCl did not affect the DFS value (Figure 3). The diminution in DFS value due to the addition of NaCl can be attributed to its ability to attract water, thereby reducing the capability of the soil to swell and shrink as it reacts with the soil particles [22].

Table 2. Combinations of materials and their corresponding proportions.

Materials	Proportions
BCS	100
Soil: WFS	93:7
Soil: WFS	86:14
Soil: WFS	79:21
Soil: WFS	72::28
Soil: NaCl	98:2
Soil: NaCl	96:4
Soil: NaCl	94:6
Soil: NaCl	92:8
Soil: WFS: NaCl	77:21:2
Soil: WFS: NaCl	75:21:4
Soil: WFS: NaCl	73:21:6
Soil: WFS: NaCl	71:21:8

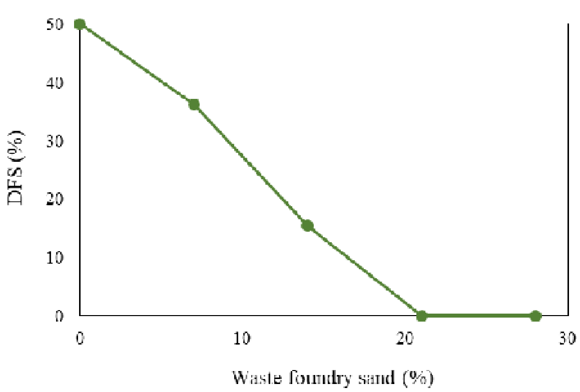

Figure 2. DFS for WFS-stabilized BCS.

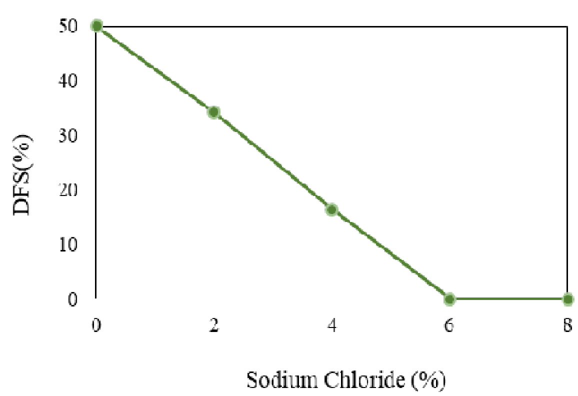

Figure 3. DFS for NaCl-stabilized BCS.

4.2. Consistency limits

Consistency limits were assessed for black cotton soil (BCS) and its various combinations with WFS and NaCl, individually and in combination with each other. The inclusion of 21% WFS to BCS resulted in a decrease in the LL from 70% to 35.2% and a reduction in the I_p from 40% to 23% (Figure 4). The presence of coarser WFS particles can disturb the soil structure and decrease its cohesion, leading to a decrease in both the liquid limit and plastic limit (Kale *et al.*, 2019). When NaCl was added to BCS in increasing amounts, the liquid limit of the composite decreased from 71% to 31%, and the plasticity index reduced from 40% to 19.4% with a NaCl content of 6% (Figure 5). The addition of NaCl to soil can alter its structure, resulting in changes in its ability to absorb and retain moisture. Consequently, both the liquid limit and plastic limit of the soil may decrease [25]. Furthermore, the combined effect of NaCl (in varying amounts) and WFS (21%, selected as the optimal content based on differential free swell) further diminished the LL and I_p (Figure 6). The LL attained 23%, and the I_p reached 20% for the BCS composite containing 6% NaCl and 21% WFS. The reason for this could be that the thickness of the double diffuse layer was further decreased by the combined impact of WFS and NaCl.

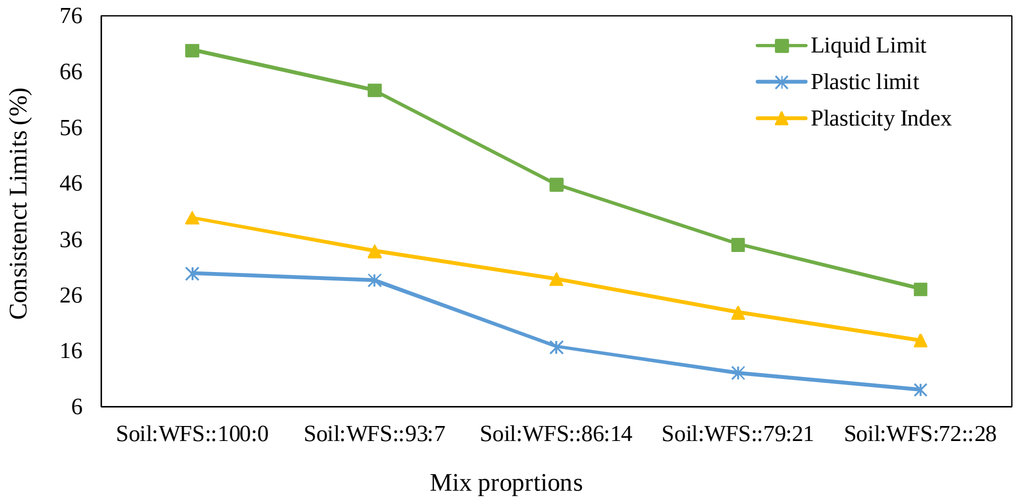

Figure 4. Consistency limits for WFS-stabilized BCS.

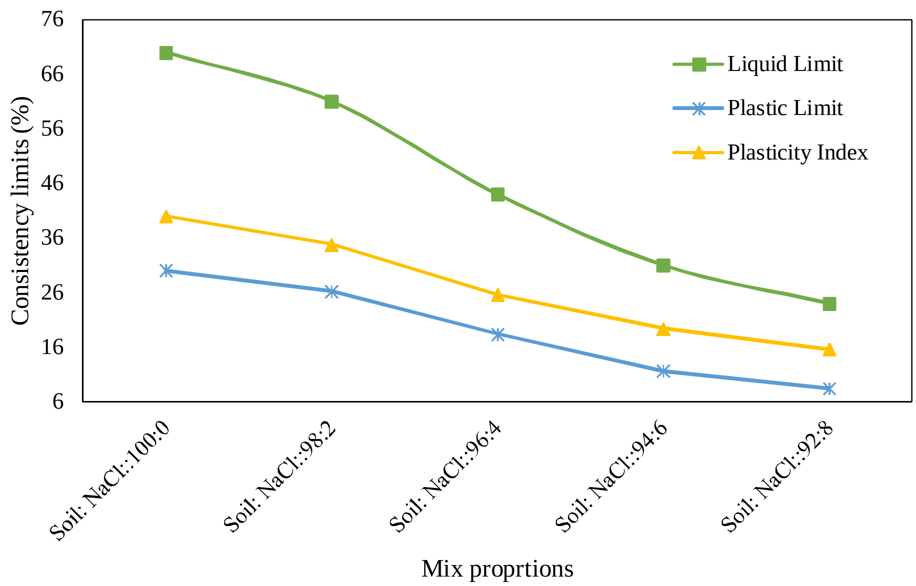

Figure 5. Consistency limits for NaCl-stabilized BCS.

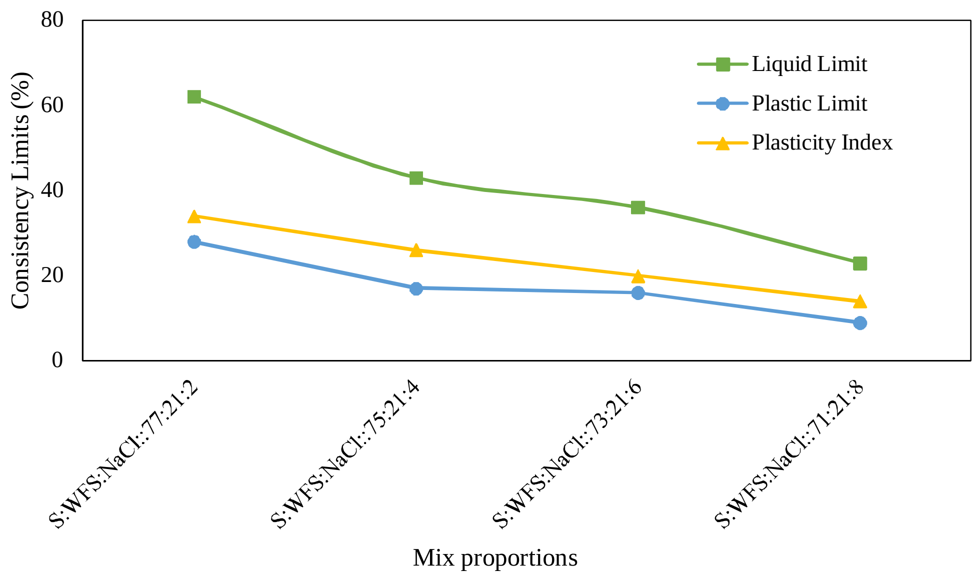

Figure 6. Consistency limit for WFS and NaCl-stabilized BCS.

4.3. Compaction

Proctor test was enacted to obtain the OMC and MDD of black cotton soil. It was noticed that the MDD and OMC values of the black soil were 20% and 1.56 g/cc consecutively.

4.3.1. Effect of addition of WFS to BCS

To examine the impact of integrating WFS on the compaction criteria of BCS, varying amounts of 7, 14, 21, and 28% WFS were added. The outcome of compaction test indicated that the inclusion of WFS led to an expansion in both OMC and MDD values for all percentages. Specifically, when 21% WFS was added, the OMC of the mix increased from 20% to 23%, and the MDD increased from 1.53 g/cm^3 to 1.76 g/cm^3 (as depicted in Figure 7). The increase in MDD can be attributed to the larger surface area of WFS particles compared to soil particles. Conversely, the increase in OMC can be imputed to the occurrence of bentonite in the WFS, which is rich in montmorillonite and has a high water-holding capacity, thus increasing OMC [24,26,27].

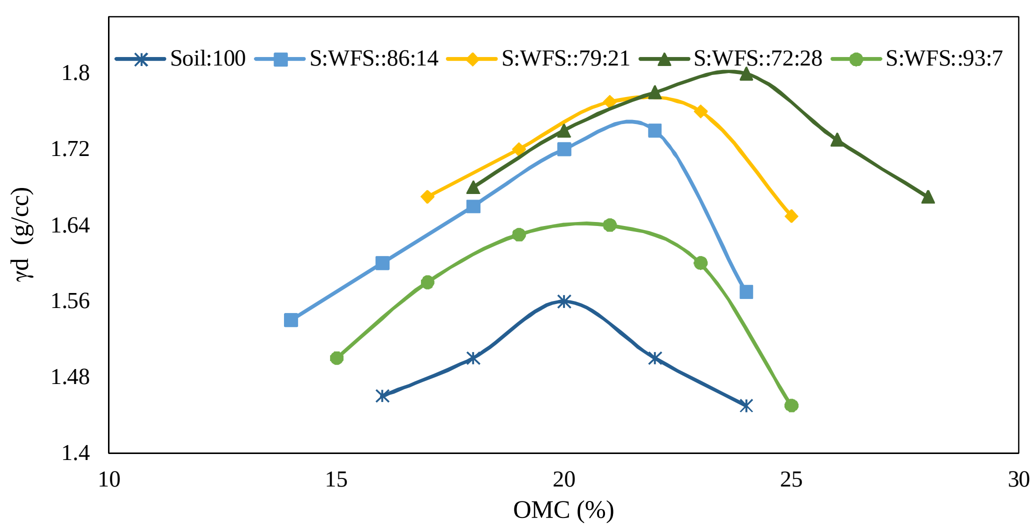

Figure 7. Soil compaction curves with different levels of WFS content.

4.3.2. Effect of addition of Nacl to BCS

Different amounts of NaCl (2%, 4%, 6%, and 8%) were employed to examine the impact of NaCl accumulation on the compaction properties of BCS. It was observed that for all NaCl percentages (as depicted in Figure 8), the MDD value increased, while the OMC value diminished. The decline in the optimum moisture content can be accredited to the hygroscopic nature of sodium chloride. This property allows NaCl to attract and retain water molecules from its surroundings, resulting in a diminution of the OMC value. The enhancement in maximum dry density can be primarily attributed to the influence of NaCl on the soil's pore water chemistry, which leads to changes in the interparticle forces of the soil. Similar behaviour has been studied by several investigators [21,22,28].

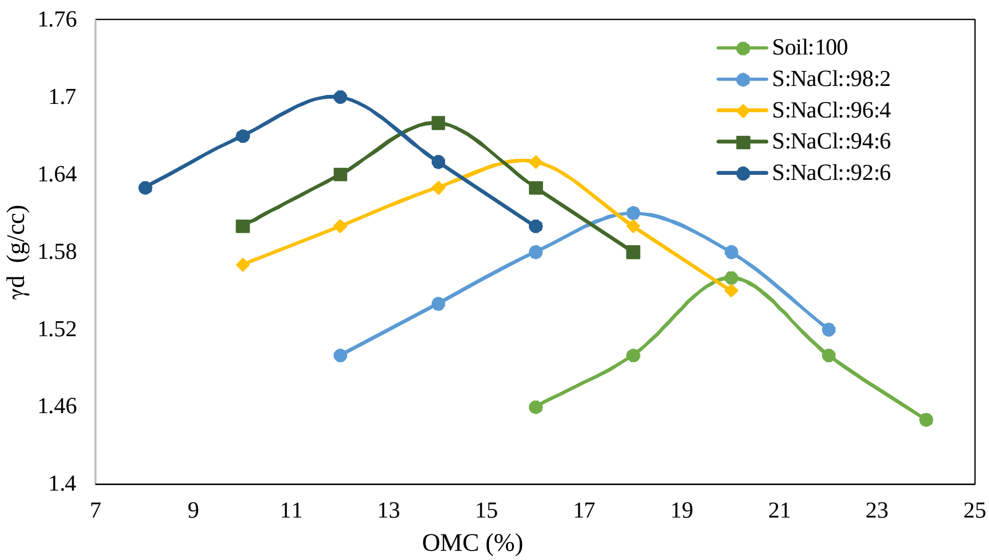

Figure 8. Soil compaction curves with different levels of NaCl content.

4.3.3. Effect of addition of WFS and NaCl to BCS

To inspect the impact of NaCl on compaction, varying amounts of NaCl such as 2%, 4%, 6%, and 8% were added to the optimum soil: WFS (21%) mix. The results exhibited that the addition of NaCl led to an upsurge in the values of MDD, while the OMC value diminished slightly for the entire proportion of NaCl. When 6% NaCl was added, the composite's OMC value lessened from 21% to 19%, and the MDD increased from 1.78 g/cm^3 to 1.85 g/cm^3 (as depicted in Figure 9). The decrease in optimal moisture content can be attributed to the hygroscopic properties of sodium chloride, which enable it to absorb and retain water molecules from the surrounding environment. This results in a decrease in the OMC. The increase in the maximum dry density is primarily due to the influence of NaCl on the pore water of the soil, which causes changes in the interparticle forces within the soil [20,26].

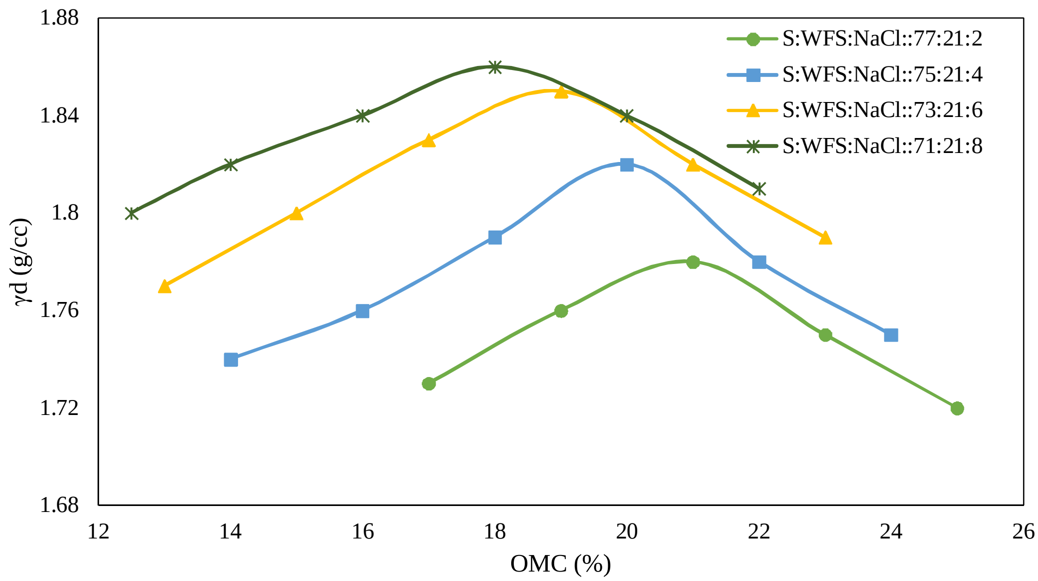

Figure 9. BCS: WFS soil compaction curves with varying levels of NaCl content.

4.3.4. CBR

The soaked CBR value of black soil alone was ascertained to be only 1.93%, which is insufficient for it to be suitable in a sub-grade. Therefore, it is necessary to stabilize the soil to increase its CBR value. The addition of WFS material to BCS in varying amounts (7%, 14%, 21%, and 28%) resulted in an enhancement of the CBR value. When 21% WFS was added, the resulting soaked CBR value was 7.6%. In addition, the addition of NaCl in varying amounts (2%, 4%, 6%, and 8%) to the optimum BCS: WFS mixture also increased the CBR value to a maximum of 3.2, 4.6, 5.8 and 6.2, respectively. However, the CBR value for the optimum combination of BCS:WFS:NaCl (73:21:6) was approximately 10.8%. Therefore, this combination can be used as a sub-grade material. The angular configuration and significant density of WFS can enhance the stability and structure of soil by occupying empty spaces and augmenting soil density. Additionally, NaCl can promote soil compaction by raising soil moisture levels and diminishing the presence of air voids. Similar behaviour has been documented by several scholars [22, 26].

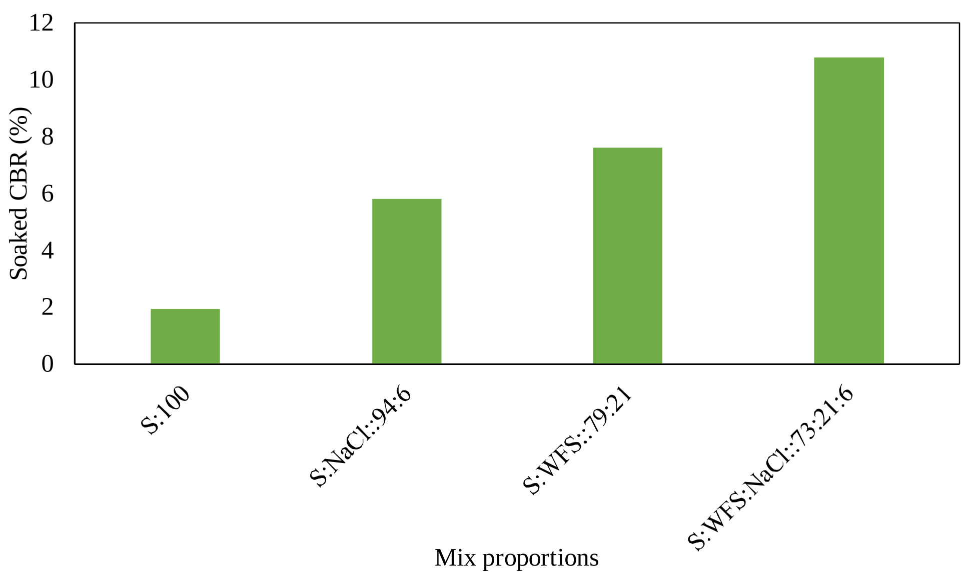

Figure 10. Optimal mix proportions and corresponding CBR values.

4.4. Design of pavement using IIT PAVE

In India, flexible pavements make up 95% of the transportation network, while concrete pavements account for less than 5%. When designing a flexible pavement, two essential factors to be considered are the vehicular traffic and subgrade parameters. The thickness of the pavement is dependent on the CBR value, and as the soaked CBR value rises, the pavement thickness reduces, resulting in a reduction in the bitumen content needed, making the construction process economical. To investigate the impact of modifying the CBR value on the thickness of pavement, the current study employed IITPAVE software.

The IITPAVE software is specifically developed to analyze linear elastic layered pavement systems using a mechanistic analytical approach. Its primary goal is to determine the optimal thickness of the pavement structure and its individual structural components, to support projected traffic loads and maintain adequate pavement performance in current climatic conditions. This software utilizes a consistently distributed single load on the road surface to calculate the strains, stresses, and deflections occurring at various points in the pavement.

Table 2 displays the input values for the software. It is necessary to assume that the overlay thickness results in a stress/strain level that is within the allowable limits.

Table 3 displays the allowable horizontal tensile strain (εt) and allowable vertical compressive strain (εv), which are calculated using IITPAVE. In modifies black cotton soil, the values of εt and εv, which respectively cause fatigue cracks and rutting, are reduced compared to untreated soil. As the CBR (California Bearing Ratio) of the sub-grade increases, the necessary design thickness is reduced, resulting in improved serviceability (Table 3) for the same design traffic. The reduction in thickness occurs almost uniformly as the CBR increases, and for all values of CBR, the total thickness increases as traffic volume increases from 1000 to 5000 CVPD (commercial vehicles per day). Consequently, as the layer thickness decreases with enhanced CBR, the cost of pavement construction reduces significantly.

Table 3. Assumed values for flexible pavement.

Input name	Value
Carriageway width after Construction	Single lane
Classification of road	Major district road (MDR)
Design life (N)	15 years
Growth rate (R)	5%
Terrain	Plain
Construction period	2 years

Table 4. Allowable and actual strain for various optimum combinations obtained from IITPAVE.

Optimum combinations	Design CBR (%)	CVPD (both side)	Design traffic		Layer thickness (in mm)	Allowable strain (in micro-strain)		Actual strain (in micro-strain)	
			For 15 years (msa)	For 5 years (msa)		Tensile strain at the bottom of bituminous layers	Vertical compressive strain at the top of sub-grade	Tensile strain at the bottom of bituminous layers	Vertical compressive strain at the top of sub-grade
S:N::94:6	5.8	1000	14.77	6.3	724.34	296	405	115	194
		3000	76.59	32.69	786.87	173	301	152	242
		5000	217.11	92.66	878.77	152	269	120	231
S:WFS::79:21	7.2	1000	14.77	6.3	716.82	296	405	115	194
		3000	72.95	31.13	764.74	173	301	115	194
		5000	127.64	54.48	832.77	152	269	115	194
S:WFS:N::73:21:6	7.8	1000	14.77	6.3	702.68	296	405	204	238
		3000	130.27	55.6	742.36	173	301	84	155
		5000	121.58	51.89	812.6	152	269	84	155

5. Conclusions

1. The geo-technical testing results indicate that the incorporation of 21% WFS and 6% sodium chloride (NaCl) is suitable for designing subgrades for low volume flexible pavements.
2. The incorporation of WFS and NaCl into BCS effectively reduces DFS to zero. Furthermore, adding WFS and NaCl reduces Ip, minimizes both swelling and shrinkage, and thus enhances consistency limits.
3. The incorporation of WFS into black cotton soil increases the OMC, while the addition of NaCl and a combination of WFS and NaCl reduces the OMC. Also the MDD improves when waste

foundry sand and sodium chloride are incorporated to BCS individually or together.

4. The inclusion of waste foundry sand and sodium chloride into BCS, either individually or in combination, leads to an enhancement in the soaked CBR value. This indicates that these materials are suitable for constructing subgrades for flexible pavements.
5. These findings suggest that the addition of 21% WFS and 6% NaCl to BCS is a cost-effective solution for construction of pavements as it improves the robustness of the subgrade layer and reduces construction costs for flexible pavement design. Therefore, it can be concluded that this optimal combination of materials is a practical and cost-effective solution for pavement construction.

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یک رویکرد جامع مرور ادبیات برای ارزیابی تأثیر احتمالی استراتژی‌های پس از بازسازی به‌کار رفته در معادن متروکه

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چکیده:

خواص انبساط و انقباض خاک پنبه سیاه، ساختن سازه‌ها بر روی آن را به یک کار چالش برانگیز تبدیل می‌کند. از این رو، اصلاح رفتار انبساط و انقباض آن برای مناسب ساختن خاک پنبه سیاه برای اهداف ساختمانی ضروری است. هدف این مطالعه ارزیابی ویژگی‌های ژئوتکنیکی خاک پنبه سیاه از طریق آزمایش‌های آزمایشگاهی، ترکیب شن و ماسه ریخته‌گری زباله (WFS) و کلرید سدیم (NaCl) برای استفاده از ترکیب به عنوان مواد زیر درجه است. تورم آزاد دیفرانسیل، محدودیت‌های قوام، تست استاندارد پروکتور و آزمون‌های نسبت باربری کالیفرنیا (CBR) با مقادیر متفاوتی از هر دو ماده انجام می‌شوند. آزمایش‌های آزمایشگاهی نشان می‌دهد که افزودن مقدار مناسب ماسه ریخته‌گری زباله، کلرید سدیم یا هر دو، خواص ژئوتکنیکی خاک پنبه سیاه (BCS) را بهبود می‌بخشد. علاوه بر این، با استفاده از مقادیر CBR به دست آمده، ضخامت روسازی انعطاف پذیر با نرم افزار IITPAVE طراحی شده و بر اساس توصیه‌های IRC: 37-2018 ارزیابی می شود. تجزیه و تحلیل نرم افزار کاهش ضخامت روسازی را برای سطوح مختلف وسایل نقلیه تجاری در روز مانند 1000، 2000 و CVPD 5000 در همه ترکیب‌ها نشان می‌دهد. این مخلوط نه تنها به مسائل مربوط به خاک پنبه سیاه می‌پردازد، بلکه یک راه حل اقتصادی برای تثبیت خاک ارائه می‌دهد و ثابت می‌کند که پایدار است زیرا شامل استفاده از مواد زائد مانند ماسه ریخته گری زباله می‌شود.

کلمات کلیدی: خاک پنبه سیاه، مواد زائد، درجه فرعی، CBR، IIT PAVE.