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Research paper

Influence of blending proportion on mechanical and microstructural properties of cement-stabilized full-depth reclamation base

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ABSTRACT

This study investigates the influence of various blending proportions (coarse: fine), varying cement dosages, and curing durations on the mechanical behavior of cement stabilized full depth reclaimed (FDR) pavement materials to be used as a base layer. The FDR process promotes sustainability by recycling in-place pavement layers, reducing dependence on virgin aggregates, and minimizing environmental impacts. Laboratory investigations are carried out on five blending proportions (80:20, 70:30, 60:40, 50:50, and 40:60) stabilized with 3%, 4%, and 5% cement contents by dry weight. Specimens are tested at curing ages of 7, 14, and 28 days to evaluate strength development. The testing program includes unconfined compressive strength (UCS), flexural strength (FS), and indirect tensile strength (ITS), in addition to ultrasonic pulse velocity (UPV) for non-destructive evaluation. Microstructural performance is examined through scanning electron microscopy (SEM) and X-ray diffraction (XRD). Results showed that cement stabilization distinctly improved strength with the 70:30 coarse-to-fine blend at 5% cement, achieving the highest UCS (10.25 MPa), FS (1.17 MPa), and ITS (0.67 MPa) after 28 days. UPV values increase consistently with higher cement and coarse aggregate contents, ranging from 1920 m/s to 2891 m/s. SEM and XRD confirmed the formation of calcium silicate hydrate (C-S-H) gel, calcite, alite, and muscovite, which enhanced particle interlock and reduced porosity. The findings highlight that optimizing aggregate gradation and binder dosage can produce durable, resource-efficient base layers, and that UPV offers a practical tool for in-field quality assessment.

1. Introduction

The growing global focus on sustainable infrastructure development has encouraged the implementation of innovative and ecofriendly methods for pavement maintenance and rehabilitation. Full-depth reclamation (FDR) stands out as an economical and environmentally friendly technique, especially effective for restoring deteriorated pavements. This *in situ* recycling technique transforms existing pavement layers into a stabilized base, significantly reducing the need for virgin aggregates, minimizing construction waste, and lowering environmental degradation [1,2]. By utilizing reclaimed material with local materials [3,4], and minimizing long-distance transportation, FDR also contributes to reduced greenhouse gas emissions, aligning with global sustainability goals.

In India, where high-quality natural aggregates often need to be hauled from distances exceeding 100 kilometers, especially in northern regions, the environmental and economic burdens of extraction and transportation are considerable. Recognizing these challenges, government agencies have begun promoting the use of FDR technology with reclaimed pavement materials as a sustainable alternative. When combined with Ordinary Portland Cement (OPC), FDR involves pulverizing existing pavement layers on-site, mixing them uniformly with cement and water, and compacting the blend to form a Cement Treated Base (CTB). This process enhances mechanical properties such as stiffness and strength, while also reducing overall transportation and plant operation costs, making FDR an efficient and sustainable pavement rehabilitation strategy.

Moreover, the adaptability of FDR to varying pavement conditions and material compositions makes it particularly suitable for low to medium volume roads [5], which constitute a significant portion of rural and regional networks in India. Incorporating cement as a stabilizing agent enhances durability, fatigue resistance, and load bearing capacity,

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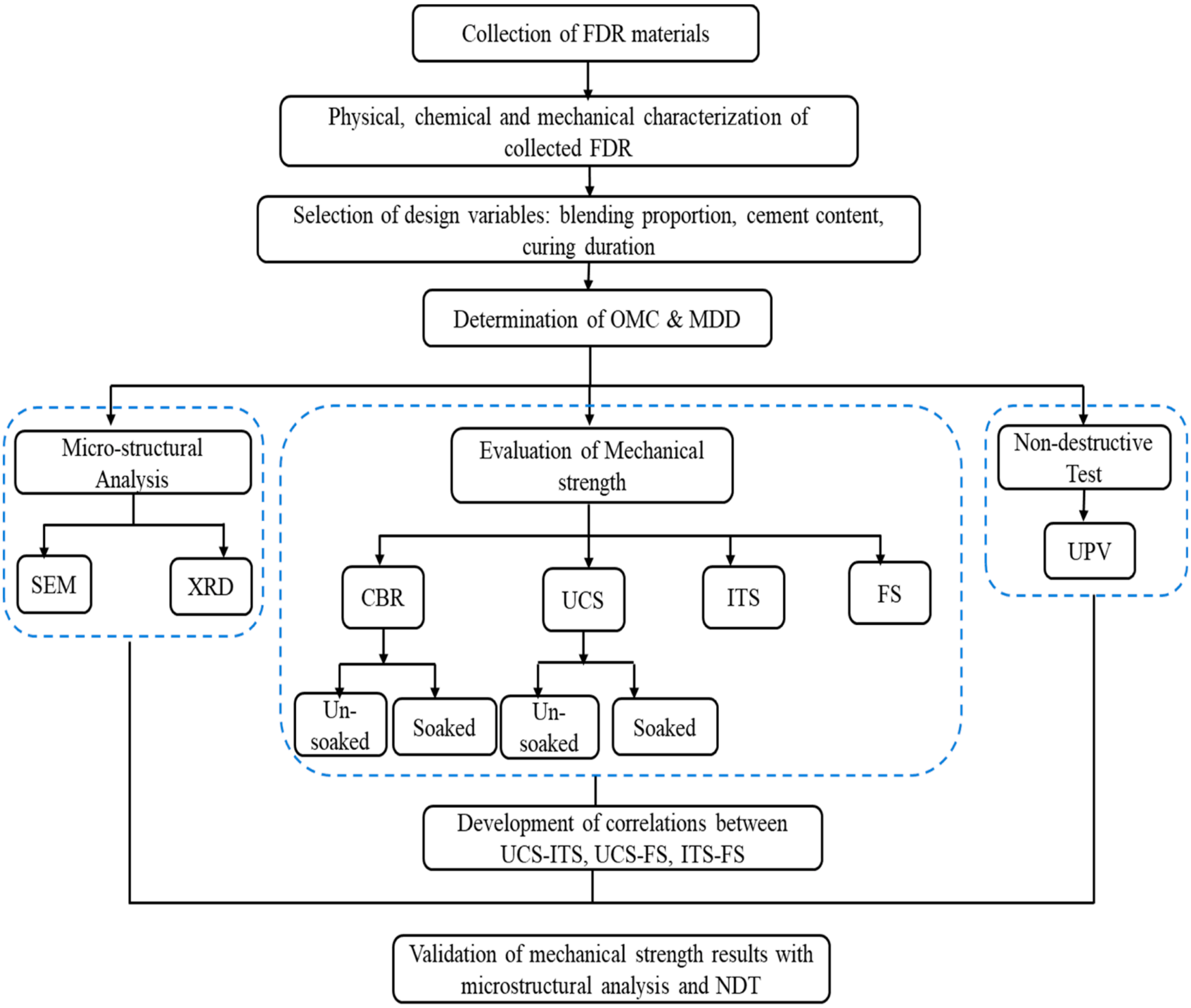


Fig. 1. Schematic representation of the research methodology.

extending rehabilitated pavements' service life. With increasing emphasis on circular economy principles and sustainable construction practices, FDR addresses the challenges of material scarcity and environmental impact but also presents a viable pathway toward resilient and resource efficient pavement infrastructure.

The overall performance of cement-stabilized FDR is governed by several design parameters, including cement content, moisture conditions, curing time, and most notably, the aggregate gradation. The ratio of coarse to fine particles in the blended mix plays a crucial role in determining key properties such as load bearing capacity, shrinkage behavior, fatigue performance, and long-term durability. Therefore, selecting an appropriate blending proportion is essential for achieving a structurally sound and sustainable pavement base [3].

1.1. Literature review

Full-depth reclamation (FDR) is a sustainable pavement rehabilitation method that reuses existing pavement layers, enhancing structural performance. The application of cement as a stabilizing agent significantly improves the strength, durability, and crack resistance of the FDR materials [6,7]. Several studies, such as [8] have investigated how cement stabilization influences the mechanical characteristics of reclaimed base materials. Mechanical properties are influenced by compaction behavior, particularly the relationship between Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), with cement stabilization often increasing OMC and slightly reducing the MDD [9,10]. Maintaining an optimal moisture content is critical to achieving uniform compaction and reducing the risk of shrinkage cracks. Studies have also highlighted the importance of precise mix design and field compaction to ensure the best performance of stabilized materials [11,12].

Cement stabilized FDR materials show significantly higher California Bearing Ratio (CBR) values, making them suitable for base layers [11] The Unconfined Compressive Strength (UCS) also improves with higher cement content and curing duration, with studies confirming its correlation with binder content [12–18] Tensile strength evaluated through the flexural strength (FS) and the Indirect Tensile Strength (ITS) test, increases with cement dosage and curing, reducing susceptibility to reflective cracking [19–21]Enhanced tensile strength improves resistance against reflective cracking [22,23], making stabilized materials more durable in pavement applications [24]. Cement -stabilized layers also demonstrate better fatigue life under repeated loading, making them viable for low volume roads. Biopolymers enhance soil strength, reduce shrinkage, and support vegetation growth [25]. Bio-based agents such as enzymes and plant polymers offer eco-friendly stabilization options [26]. Hybrid use of rice fiber with nanoclay improves strength, ductility, and bonding in clayey soils [27]. Future research should focus on optimizing mix designs, exploring supplementary stabilizers, and applying non-destructive testing methods for better performance evaluation [12,18,20,21].

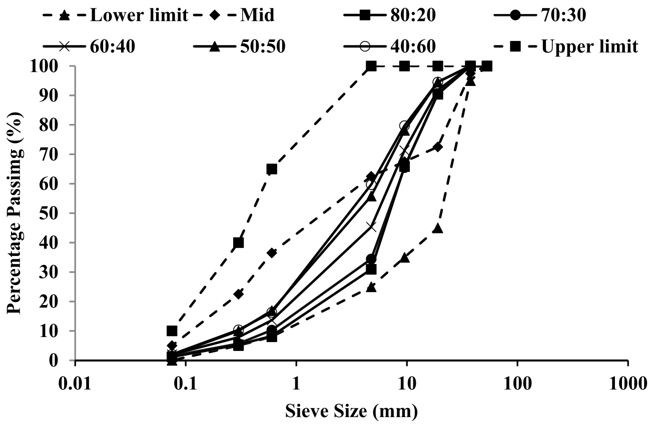


Fig. 2. Gradation curve of all the blending ratios of FDR material.

1.2. Research significance

Numerous investigations have explored the mechanical behavior of full-depth reclaimed (FDR) materials in both untreated and stabilized forms, using parameters like the California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) to evaluate their suitability for low-volume road applications. Although numerous studies have investigated the mechanical properties of cement-stabilized FDR materials, most have primarily focused on the effect of cement dosage or curing conditions, with limited attention given to aggregate gradation. Aggregate blending proportion directly influences packing density, particle interlock, and the formation of cementitious bonds, yet its role in optimizing both mechanical performance and microstructural development remains underexplored. Moreover, while non-destructive testing methods such as ultrasonic pulse velocity (UPV) have been studied in cementitious materials, their application as predictive tools for strength assessment in FDR bases has not been comprehensively validated. This study addresses these gaps by systematically evaluating the influence of blending ratio, cement content, and curing duration on UCS, FS, and ITS, supported by SEM, XRD based microstructural performance analysis, and establishing predictive correlations with UPV results for practical field implementation.

2. Materials and experimental design

This section explains the materials utilized in this study, the procedure of preparing test specimens, and the testing methods employed. Fig. 1 illustrates the flow chart outlining the research methodology adopted in this study.

2.1. Materials selection and characterization

2.1.1. Full-depth reclaimed material

Full-depth reclaimed (FDR) materials used in this research have been sourced from a nearby village road. These materials were carefully reclaimed, transported to the laboratory, and separated using different sieves to create two stockpiles. The gradation of each stockpile, containing aggregates of varying sizes, was analyzed to ensure a well-graded distribution. The gradation was adopted in accordance with Indian specifications, following the grading requirements specified in MoRTH Table 400-4. Using the STAB software, a few blending proportions (coarse: fine) such as 80:20, 70:30, 60:40, 50:50, and 40:60 were chosen to optimize the material composition and study the effect of different blending combinations. Based on the Unified Soil Classification System (USCS), IS:1498,1970, all the blending proportions were categorized as GW, representing well-graded gravel. A representative grain size distribution curve for full-depth reclaimed material of all the blending proportions is shown in Fig. 2.

Table 1
Physical and mechanical characteristics of the different blending combinations of untreated FDR materials.

Physical Properties	80:20	70:30	60:40	50:50	40:60	Standard methods
Gravel (%)	69.08	65.58	54.71	44.21	40.29	ASTM D (2487). -11(2011)
Sand (%)	29.75	32.84	43.31	53.88	57.68	ASTM D (2487). -11 (2011)
Silt and clay (%)	1.17	1.48	1.98	1.91	2.03	ASTM D 2487-11 (2011)
OMC (%)	5.901	6.023	6.178	6.543	6.820	IS:2720 (Part 8) (1983)
MDD (gm/cc)	2.178	2.167	2.161	2.154	2.149	IS:2720 (Part 8) (1983)
Soaked CBR (%)	62	64	59	52	48	IS:2720 (Part 16) (1987)
UCS (MPa)	1.4	1.49	1.39	1.37	1.32	IRC: SP-72 (2015)

Table 1 presents the physical and engineering properties of the various blends, such as particle size distribution, modified proctor compaction results, unsoaked and soaked California bearing ratio (CBR), and Unconfined compressive strength (UCS) of the untreated FDR materials. Fig. 3 **[a-g]** illustrate the image of macro, micro characterization of untreated FDR and cement. Various geotechnical properties test was conducted on the finer fractions of the FDR materials, such as Atterberg limits, plasticity index, free-swell index, soil classification, and the corresponding results, are summarized in Table 2. Also, various physical properties tests were conducted on the coarser fractions of the FDR materials, such as specific gravity, water absorption, aggregate impact value, crushing value, abrasion resistance, and shape characteristics and the corresponding results are summarized in Table 3.

2.1.2. Cement

In this investigation, Ordinary Portland Cement (OPC) grade 43 was utilized as the primary stabilizing material, in accordance with the guidelines provided in IRC: SP 20 (2002). The specific gravity of the cement was measured following the procedure outlined in IS:1727 (1967), yielding a value of 2.97 g/cm^3.

2.2. Preparation of the sample

A particle size distribution analysis was performed on the Full depth reclamation (FDR) samples. The materials were initially separated based on their individual grain sizes and subsequently recombined in specific proportions to achieve the target gradation requirements outlined in IRC: SP-89 (Part II), 2018, for cement stabilization.

To ensure uniformity across all tests, reconstituted samples with consistent gradation were utilized throughout the experimental program. The compaction behavior of the FDR materials was evaluated following the procedure outlined in IS:2720 (Part 8), 1983, and the results are summarized in

Table 1. For subsequent testing, the FDR material and cement were first dry mixed in the designated proportions. After achieving a uniform blend, the predetermined quantity of water was added to the mixture. The moistened material was then compacted in standard moulds using specified hammer weight, drop height, and compaction energy, aiming to attain the maximum dry density (MDD) corresponding to modified proctor compaction, as per the methodology described by [19,28]. The prepared specimens were left in their respective moulds for 24 h under sealed conditions to minimize moisture evaporation. Following this initial period, they were molded and subjected to curing for the designated durations using wet gunny bags to maintain adequate moisture

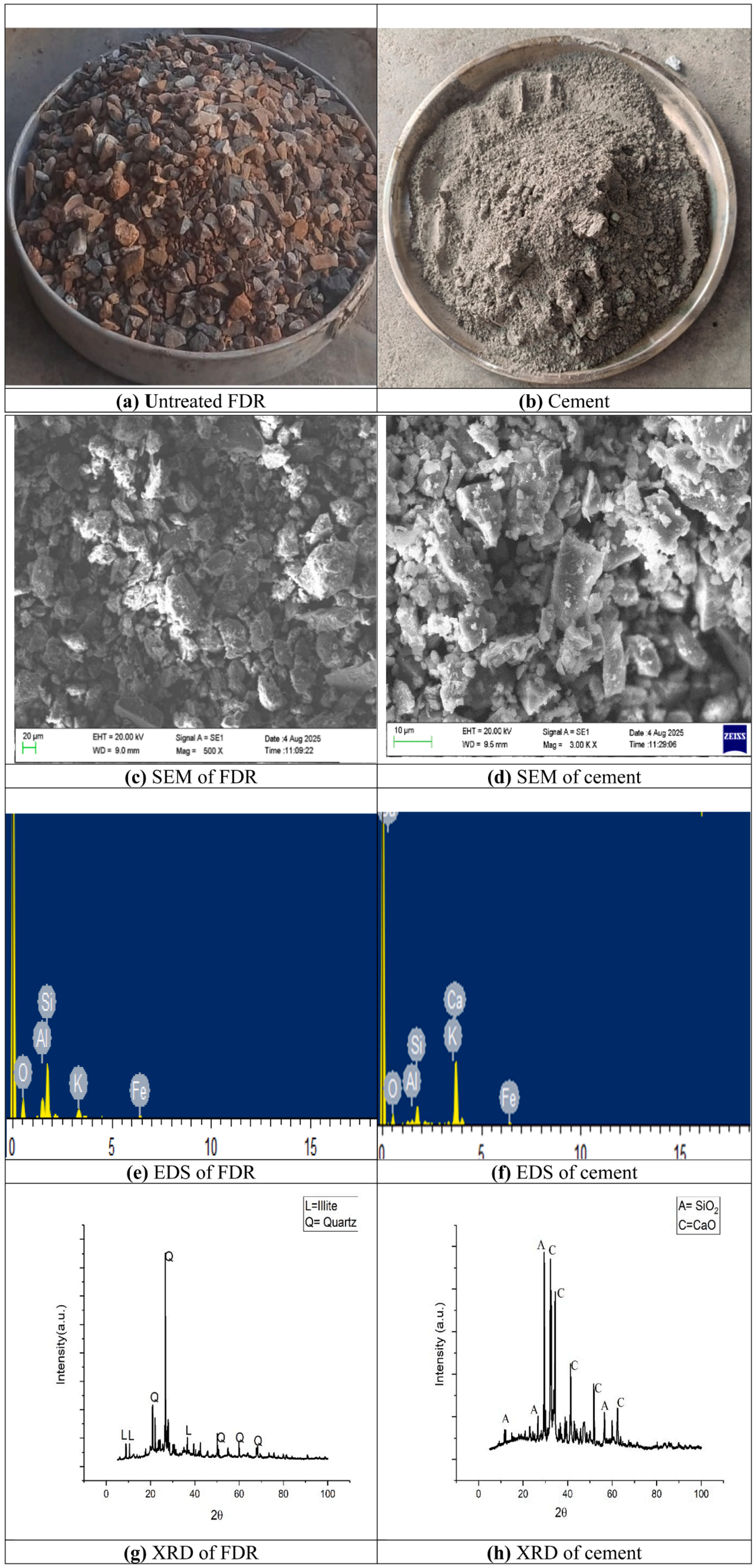


Fig. 3. Macro, micro characterization of untreated FDR and cement.

Table 2
Geotechnical properties of the FDR soil material.

Physical Properties	Results	Standard methods
Liquid limit (%)	28.1	IS:2720 (Part 5) (1985)
Plastic limit (%)	20.9	IS:2720 (Part 5) (1985)
Plasticity Index (%)	7.2	IS:2720 (Part 5) (1985)
Free swell index (%)	10	IS:2720 (Part 40) (1977)
Soil classification as per USCS	GW	AASHTO (2011)

Table 3
Physical properties of the FDR sample with the IRC codes and specifications.

Physical Properties	FDR	Specification
Aggregate impact value(dry) (%)	33.68	IS:2386 Part IV (1963)
Aggregate Crushing value (%)	24	IS:2386 Part IV (1963)
Los Angeles Abrasion value (%)	29	IS:2386 Part IV (1963)
Flakiness index (%)	15	IS:2386 Part I (1963)
Elongation index (%)	8.23	IS:2386 Part I (1963)
Specific gravity	2.721	IS:2386 Part III (1963)
Water absorption (%)	1.95	IS:2386 Part III (1963)

Table 4
Composition of FDR sample by weight (%).

Elements	FDR	Cement
SiO2	52.686	19.182
Al2O3	15.406	3.689
CaO	2.446	62.76
Fe2O3	6.944	4.694
K2O	2.959	0.765
MgO	1.115	4.218
MnO	0.131	0.108
Na2O	0.447	0.875
P2O5	0.137	-

levels. Comprehensive details regarding the specimen dimensions, curing durations, test procedures, and the number of samples used are provided in Table 4.

2.3. Test methods

The following section outlines the testing approaches used to determine the effectiveness of both un-stabilized and cement-stabilized base FDR material in pavements that are presented below:

2.3.1. Modified proctor test

Compaction tests were conducted in accordance with IS 2720 Part 8 (1983), utilizing the modified proctor method. This method employs a 4.9 kg rammer dropped from a height of 457 mm, delivering a compaction effort of 2.735 N mm/mm^3. Each sample was compacted in five layers, with 56 blows applied per layer. Prior to testing, the FDR materials were air-dried to achieve constant mass. Cement and water were then measured and incorporated into the air-dried FDR material. The dry components were thoroughly mixed before water was gradually added during continuous mixing. The quantity of cement was determined as a percentage of the air-dried FDR mass. For each specimen, moisture content was varied incrementally to determine the optimum level. The resulting maximum dry density (MDD) and optimum moisture content (OMC) for each mix are presented in Fig. 4.

2.3.2. California bearing ratio test

California bearing ratio test was conducted as per IS:2720 (Part 16), 1987 to evaluate the strength and bearing capacity of untreated and treated FDR material. Each specimen was compacted in standard moulds, and two surcharge discs of 2.5 kg each were placed on top to simulate overburden pressure. A 50 mm diameter plunger was then applied at a constant penetration rate of 1.25 mm/min. Load readings were taken at specific penetration depths to calculate the CBR value, indicating the material's resistance to deformation under load.

2.3.3. Unconfined compressive strength test

The unconfined compressive strength (UCS) test is used to determine the maximum axial stress that a sample can resist without lateral confinement. It serves as a key parameter for evaluating the strength of treated materials under both soaked and unsoaked conditions. In this study, FDR material was compacted into cube moulds, and perform the curing by wet gunny bags for various durations. Indian standards allow testing after shorter curing periods, international guidelines (AS 5101.4, 2008) recommend a 28-day curing followed by soaking. Accordingly, in this present study, soaked and unsoaked UCS tests were conducted after 7,14, and 28 days of curing to assess strength development over time, with a consistent four-hour soaking period. The experimental setup is shown in Fig. 5(a).

Table 5

2.3.4. Flexural strength test

Stabilized (or bound) materials typically demonstrate greater strength and stiffness compared to unbound layers. However, cement - stabilized materials are known to be more brittle, show limited

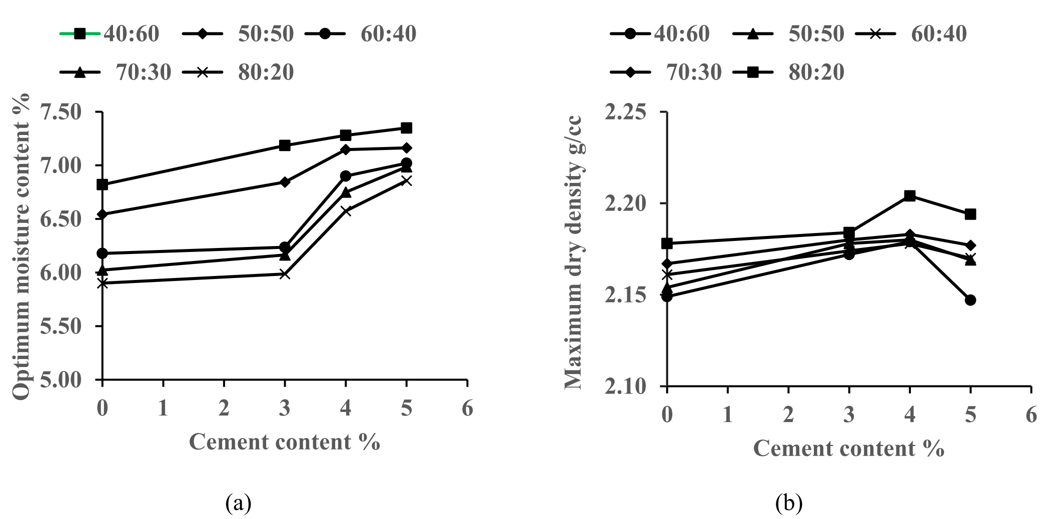


Fig. 4. Modified proctor compaction of various blending proportions of FDR mixtures, (a) Influence of cement content on optimum moisture content; (b) Influence of cement content on maximum dry density.

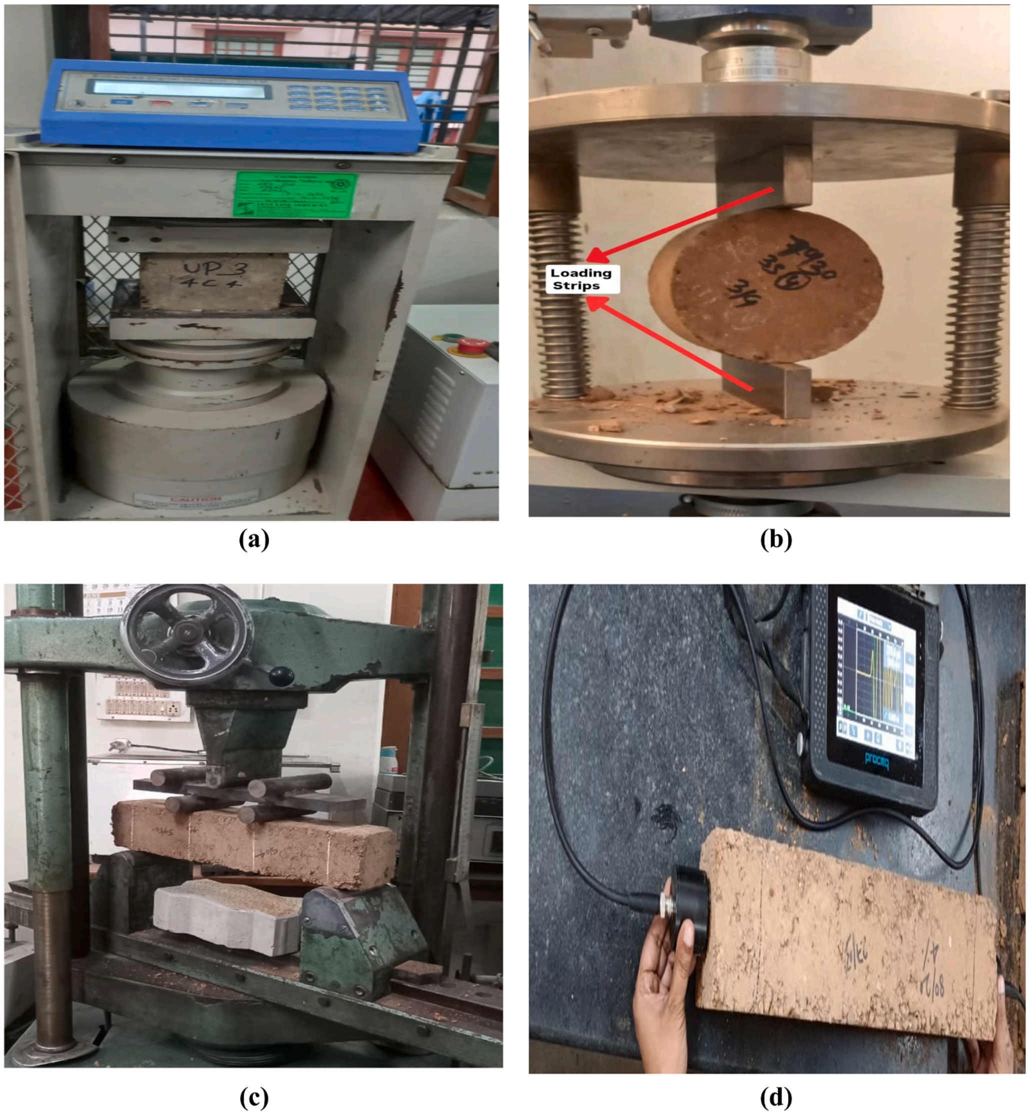


Fig. 5. Tests in progress (a) UCS (b) ITS (c) FS (d) UPV.

Table 5
Test procedure to evaluate the mechanical strength of FDR samples.

Tests to be conducted	Specimen shape	Specimen size	Blending proportion	Cement content	Curing periods	Number of tests
CBR	Cylinder	d=150 mm h=125mm	5	3,4,5	Unsoaked, 4 days soaked	3 × 5 × 3 × 2=90
UCS test	Cube	l=150mm b=150mm h=150mm	5	3, 4, 5	7 days, 7 days+4 h soaking, 14 days, 14 days + 4 h soaking, 28 days, 28 days+ 4 h soaking	3 × 5 × 3 × 6=270
ITS test	Cylinder	d=100mm h=60mm	5	3, 4, 5	7 days, 28 days	2 × 5 × 3 × 2=60
FS test	Prism	l=500mm b=100mm h=100mm	5	3, 4, 5	28 days	2 × 5 × 3=30

resistance to deformation, and are prone to significant shrinkage. The resistance of such materials to cracking is often assessed through flexural strength (FS) measurements. In this study, the FS, also referred to as the modulus of rupture, of cement-stabilized full-depth reclamation specimens, was evaluated using a four-point bending test under monotonic loading conditions after curing periods of 28 days, following the methodology outlined by [29,30] and illustrate in Fig. 5(c).This test was conducted in a stress-controlled setup at a loading rate of 690 kPa/min, as per ASTM D1635 (2012), with a span to depth ratio of 3:1. Load was applied at four points on the prism shaped FDR specimens of (100 × 100 × 500mm).

2.3.5. *Indirect tensile strength test*

Natural soils generally exhibit very low tensile strength compared to their compressive strength; however, stabilization techniques can significantly improve this property. Tensile strength can be assessed using direct, indirect, or flexural (bending) methods, but the indirect tensile strength test being widely preferred due to the difficulties associated with direct testing, which often leads to the introduction of secondary stresses. The experimental setup is shown in Fig. 5**(b)**. In this

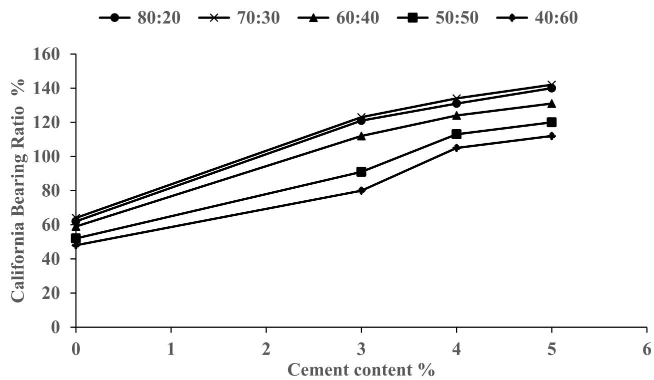


Fig. 6. Influence of blending proportion and cement content on the 4 days soaked CBR of cement stabilized FDR samples.

study, the ITS test was conducted on FDRM specimens after 7 and 28 days of curing, following the approach suggested by [31,32], under monotonic compressive loading. The tests were performed in strain-controlled mode at a deformation rate of 50 mm/min, in accordance with ASTM D6931–17 (2012). ITS values can serve as indicators of a material's resistance to rutting, thermal cracking, and fatigue, making it a valuable parameter for assessing the durability and performance of stabilized pavement layers.

2.3.6. Non-destructive test

Non-destructive test (NDT) serves as a crucial tool for quality control and assurance, enabling the evaluation of material properties without compromising their serviceability. Various simple non-destructive testing (NDT) methods, such as ultrasonic pulse velocity (UPV), rebound hammer, and seismic modulus tests, are commonly used to estimate the strength and stiffness of cement stabilized materials [33, 34]. Among these, the UPV method is regarded as more dependable, as it evaluates the elastic behavior of the entire specimen by transmitting ultrasonic waves through its internal structure, rather than being limited to surface level assessments [35]. In the present study, the ultrasonic pulse velocity (UPV) test was carried out on FDR specimens after a 28-day curing period, following the guidelines of IS:13311-1 (1992). A PUNDIT device, comprising a transducer, receiver, and digital display unit, was used to perform the test. Ultrasonic waves were generated by the transducer and received by the receiver; both were firmly fixed to the sample during testing. These components can be arranged in different configurations opposite faces (direct transmission), adjacent faces (semi-direct), or the same face (indirect). Among these, direct transmission offers the highest accuracy and sensitivity, and was therefore selected in this study to determine the pulse velocity and calculate the constrained modulus of the FDR mixtures. The experimental setup is shown in Fig. 5(d).

2.3.7. Microstructural characterization tests

Analyzing the morphology of materials provides valuable insights into their formation processes and overall quality. In this study, full-depth reclamation (FDR) mixtures stabilized with cement were examined to evaluate the influence of cement on their internal structure. X-ray diffraction (XRD) was used to identify the crystalline phases present. These microstructural investigations help in understanding the changes in mineral composition and the formation of cementitious products within the stabilized matrix. Scanning electron microscopy (SEM) was employed to study surface morphology and detect changes induced by cement stabilization, such as variations in pore size, particle arrangement, and shape. These techniques helped to assess the role of cement in enhancing the structural integrity of the reclaimed material.

3. Results and discussion

This section presents the experimental findings and provides an interpretation of the notable trends and key observations.

3.1. CBR of FDR mixes

According to IRC: SP 20 (2002), materials intended for the sub-base and base layers of low-volume roads should meet minimum soaked CBR requirements of 15% and 100%, respectively. Since these layers are often exposed to moisture, evaluating CBR under soaked conditions is necessary. Saturation typically reduces CBR values due to the loss of surface tension within the material structure. In this study, untreated FDR samples of all the blending proportions fulfilled the sub-base requirements under soaked conditions as per the IRC specifications. As shown in Fig. 6, with the addition of cement, a consistent improvement in the soaked CBR values of FDR mixtures was observed. The CBR gain was evaluated after four days of soaking to assess the improvement in strength due to cement stabilization in comparison to the untreated FDR mixtures. This gain reflects the strength improvement resulting from cement treatment compared to untreated FDR mixtures. A significant increase in CBR value with an increase in the blending proportion and cement content. This behavior may be attributed to the formation of optimal amounts of cementitious compounds such as C-S-H and calcium oxide, [36]. The highest CBR gain was recorded for 70:30 treated with 5% cement, reaching 142% while the lowest was observed in 40:60 treated with 3% cement, showing a gain of 80% under soaked conditions. It also illustrates how varying cement content influences the CBR performance of the stabilized FDR mixtures.

3.2. UCS of FDR mixes

3.2.1. Effect of blending proportion on UCS

Fig. 7 illustrate the Unconfined Compressive Strength at 7, 14, and 28 days curing for various blending ratios of coarse to fine aggregate (40:60, 50:50, 60:40, 70:30, and 80:20) treated with 3%, 4%, and 5% cement content, under both unsoaked and 4 h-soaked conditions. Across all curing durations, the UCS values exhibited a progressive increase with improved blending proportions, reaching an optimum at the 70:30 (coarse: fine) mix ratio. However, further increasing the coarse aggregate content in the blend to 80:20 resulted in a consistent reduction in UCS. This reduction is likely due to diminished matrix cohesion and weaker inter particle bonding, which adversely affect the structural integrity of the stabilized mixture. On the other hand, mixtures with a 40:60 ratio demonstrated lower strength, attributed to an excess of fine particles that hinder effective load transfer and matrix densification. The beneficial impact of optimized blending becomes particularly pronounced at higher cement dosages. According to IRC: SP:89,2018, the recommended minimum UCS for constructing a cement stabilized base is 4.5 MPa to 7 MPa for cement stabilized granular materials, with proper moist curing. Furthermore, it is recommended that laboratory determined UCS should be 1.1 times the target design strength 4.5 MPa to account for variability in field construction. At 5% cement content with 7 days curing all blending proportions surpassed the target UCS threshold of 4.95 MPa. Specifically, strength values exceeded 8 MPa at 7 days and 10 MPa at 28 days. It is also achieved in dry condition with 40% and lower finer material at 4% cement content. Furthermore, following 4 h of soaking, specimens with higher coarse aggregate content, particularly the 70:30 and 60:40 blends cured for 28 days at 5% cement content, maintained UCS values above the required specification of 4.95 MPa. This performance indicates enhanced water resistance and long-term durability, likely due to improved particle interlock and denser packing achieved with increased coarse aggregate fractions.

3.2.2. Effect of cement content on UCS

The UCS of all untreated FDR samples was less than 1.5 MPa. The

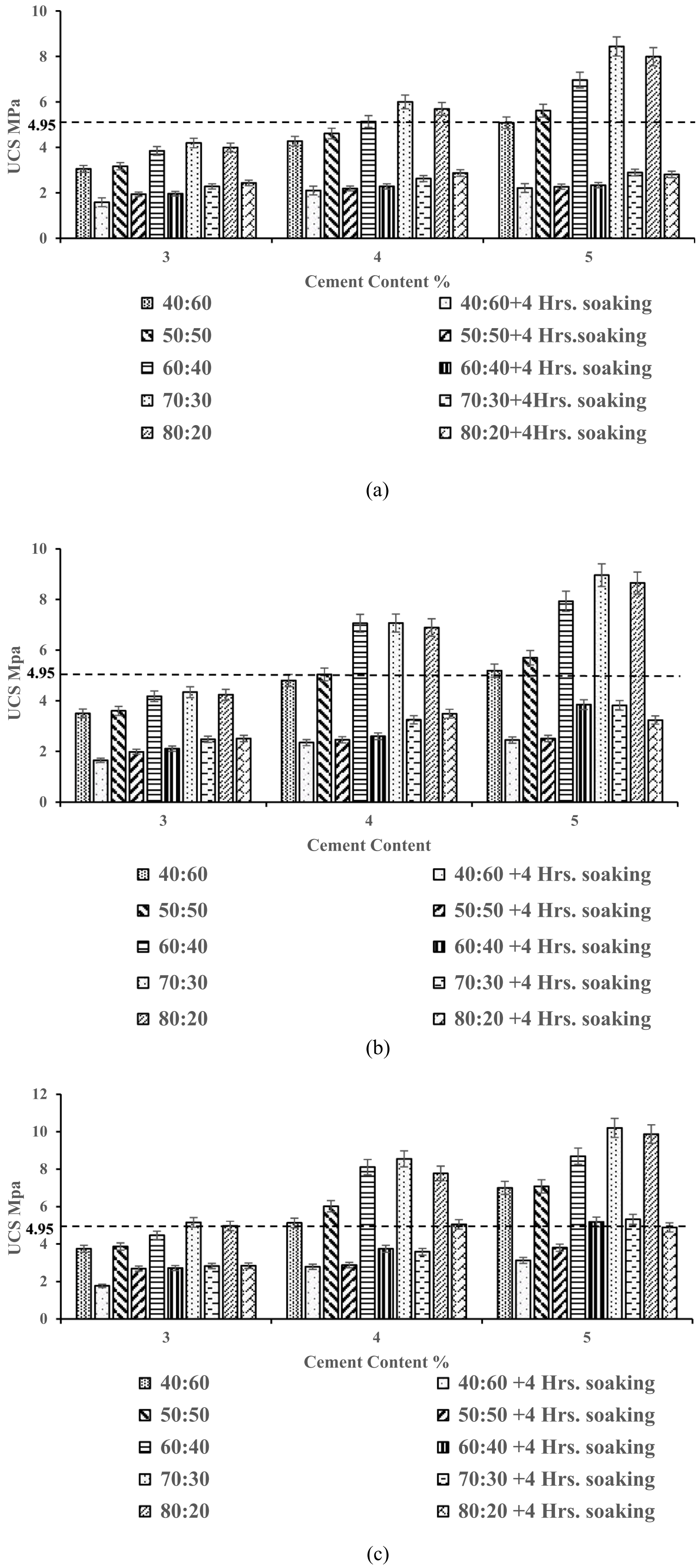


Fig. 7. Effect of cement dosage and blending proportions at various curing periods on UCS of FDR samples. (a) UCS of seven days cured FDR mixes; (b) UCS of fourteen days cured FDR mixes; (c) UCS of twenty eight days cured FDR mixes.

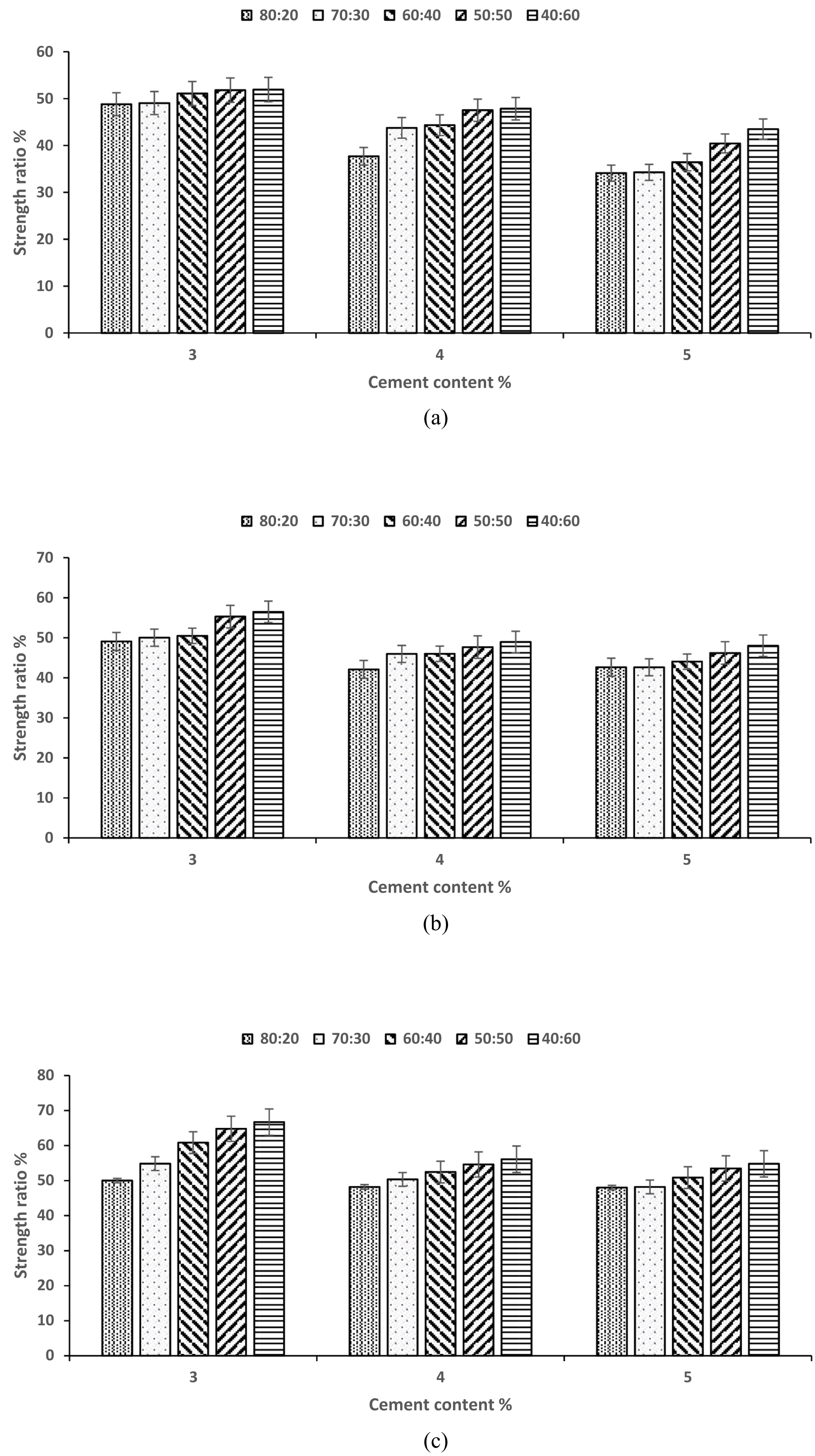


Fig. 8. Variation in the rate of strength increase in FDR samples after various curing durations (a)7 d, (b)14 d, and (c) 28 d of curing.

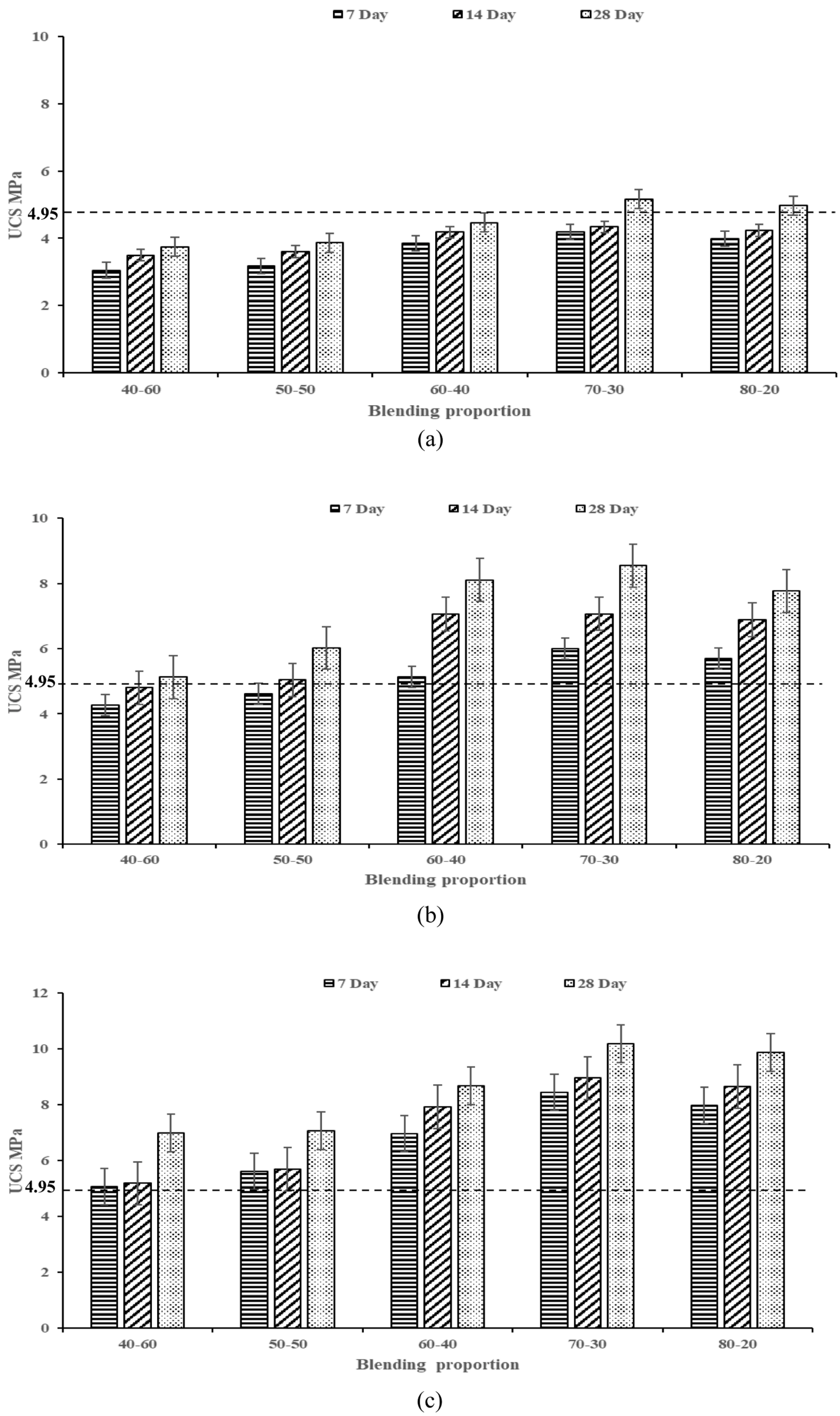


Fig. 9. Effect of curing duration on UCS of FDR smaples (a)3% cement content, (b)4% cement content, (c)5 % cement content.

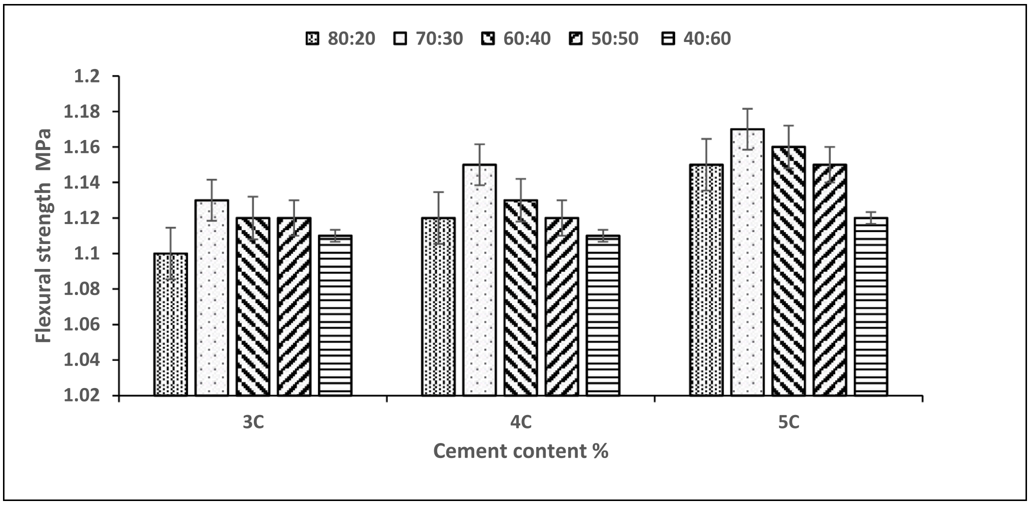


Fig. 10. FS of FDR mixes.

unconfined compressive strength (UCS) of cement-stabilized materials at 3, 4, and 5% cement content, as shown in the

Fig. 7 Clearly demonstrates the positive influence, i.e., UCS increases consistently with increasing cement content across all gradation This is expected as higher cement content promotes better hydration and binding of particles, leading to denser and stronger matrices. At 3% cement, UCS values range between 3 MPa to 6.9 MPa, depending on gradation and curing days. Increasing cement content to 4% improves UCS from 4.27 MPa to 8.770 MPa. At 5%, UCS improves from 5.082 MPa to 10.250 MPa. It observes that at 5% cement content, UCS exceeds 10 MPa for the coarser gradations. Strength gain is more pronounced between 3% and 4% cement than between 4% and 5%. Cement content has the most pronounced effect at 28 days, with UCS values for 5% cement reaching up to ~10.25 MPa in unsoaked conditions. Optimum cement content appears to be 4%, depending on the blending proportions, considering both early strengths. The increase in cement content significantly enhances UCS, particularly at longer curing periods. While 3% cement may be suitable for dry conditions, it is not reliable under soaked or field conditions. The results strongly support the use of 4% to 5% cement content for ensuring both early strength and long-term durability of stabilized full-depth reclamation FDR materials. As shown in Fig. 8 the percentage of strength ratio is greater for 28-day cured FDR samples than for 14-day and 7-day cured samples. Also, the strength gain ratio is higher in 3 % cement content than in 4% and 5 % cement content.

3.2.3. *Effect of curing durations on UCS*

The significant influence of curing durations of 7, 14, and 28 days on the strength development of cement stabilized materials is clearly illustrated in Fig. 9**.** The following analysis highlights how curing impacts the performance across different gradations and cement contents. UCS values at 7 days are moderate, ranging from 3 MPa (for 3% cement) up to 9 MPa (for 5% cement in coarser gradations). At this stage, hydration is still progressing, and strength development is incomplete. Strength continues to increase between 14 and 28 days, though the rate of gain slows. The progression highlights that longer curing leads to denser and stronger cementitious matrices due to continued hydration.

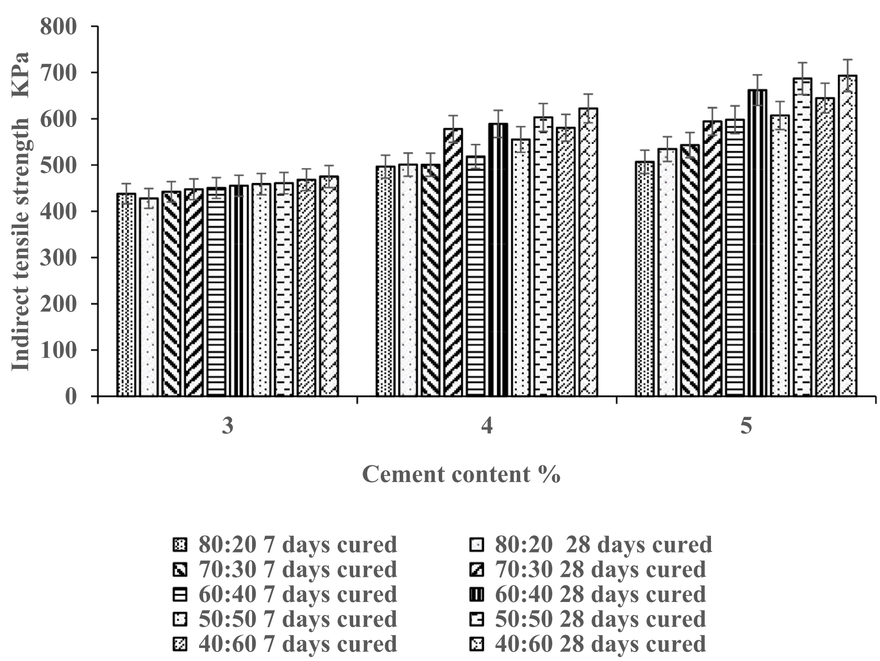


Fig. 11. Effect of blending proportion, cement content, and curing duration on ITS of FDR mixes.

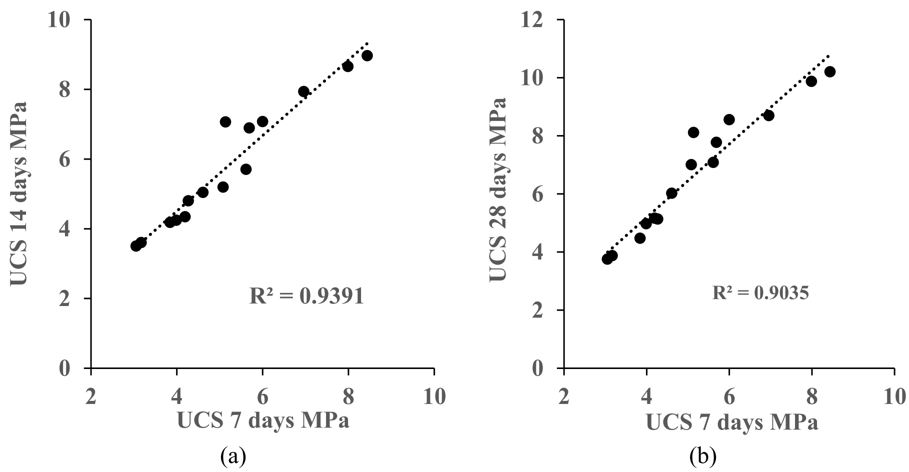


Fig. 12. Correlation between(a) 7 and 14 days UCS, (b) 7 and 28 days UCS.

3.3. Flexural strength of FDR mixes

Flexural strength tests were performed on FDR samples after 28 days of curing to determine their bending resistance and shown in Fig. 10. The results revealed that strength improved with longer curing times, indicating continued cement hydration and matrix strengthening. The 70:30 mix achieved the highest flexural strength, likely due to better particle arrangement and uniform cement dispersion. In contrast, the 80:20 mix had lower strength values, possibly because of weaker bonding and a discontinuous matrix.

3.4. Indirect tensile strength of FDR mixes

Due to the inherently low tensile strength of untreated FDR materials, their values are not included in this analysis. However, a significant enhancement in indirect tensile strength (ITS) was observed with cement addition and extended curing periods. As shown in Fig. 11**,** ITS increases proportionally with the formation of cementitious compounds, which continue to develop over time. After 28 days of curing, all FDR mixtures recorded ITS values exceeding 0.4 MPa, with a peak value of 0.67 MPa observed in 70:30 blending proportion of FDR stabilized with 5% cement.

3.5. Correlation between strength parameters

$$UCS_{14days}(MPa) = 1.0191 \times UCS_{7days}(MPa) + 0.433 \quad (1)$$

$$UCS_{28days}(MPa) = 1.1045 \times UCS_{7days}(MPa) + 0.8775 \quad (2)$$

$$UCS_{7\ days+\ 4\ Hrs.\ soaked} = 0.1925 \times UCS_{7\ days} + 1.1982 \quad (3)$$

$$UCS_{\ 14\ days+\ 4\ Hrs.\ soaked} = 0.354 \times UCS_{14\ days} + 0.8211 \quad (4)$$

$$UCS_{28\ days+4\ Hrs.\ soaked} = 0.494 \times UCS_{28\ days} + 0.0967 \quad (5)$$

The correlation between the 7 d UCS with the 14 d and 28 d UCS values is illustrated in Fig. 12. A strong linear relationship was observed, with correlation coefficients of R^2 =0.939 (Eq. 1) and R^2=0.905 (Eq. 2). These results indicate that the 28-day UCS can be reliably predicted from the 7 d UCS values for the given stabilized materials, demonstrating consistent strength development with curing age. Eqs. 3, 4, and 5 present the correlations established between the UCS values of FDR samples after 7,14, and 28 days of curing, followed by four hours of soaking and shown in Fig. 13. To evaluate the degree of bonding in the stabilized FDR mixtures, UCS ratios were computed at 7,14, and 28 days of curing, as suggested by Mohanty et al. (2023), Biswal et al. (2018a). These ratios represent the UCS of soaked specimens (after 7,14, and 28 days of curing, followed by 4 h of water immersion) relative to their corresponding unsoaked (after 7,14, and 28 days of curing). Although the samples were compacted at OMC and cured with wet gunny bags during the curing phase, their UCS values showed considerable reduction upon water immersion for four hours after the specified curing periods.

The correlation between ITS and curing duration is illustrated in Fig. 14 and expressed by Eq. 6. Furthermore, regression models have been formulated to link ITS with UCS (Eqs. 7 and 8) for both 7-day and 28-day cured FDR samples. As reflected in Fig. 15 the regression models exhibit higher R^2= 0.933 values for 7-day cured samples, indicating stronger predictive relationships at earlier curing stages.

$$ITS_{28days} = 1.344 \times ITS_{7\ days} - 144.4 \quad (6)$$

$$ITS_{7days} = 0.0341 \times UCS_{7days} + 0.3338 \quad (7)$$

$$ITS_{28days} = 0.0393 \times UCS_{28days} + 0.2832 \quad (8)$$

3.6. NDT (UPV) test

In the present study, the non-destructive test, i.e., ultrasonic pulse velocity (UPV), has been performed on all the blending proportions of the Cement -stabilized FDR mixtures. IS:13311-1, 1992 was used to calculate the P-wave velocity (V_P) and constrained modulus (CM). In direct transmission mode, the V_P for the 3% cement content with a 40:60 blending ratio was 1920 m/s and increased to 2360 m/s for the 80:20 blending ratio. Similarly, increasing the cement content from 3% to 5% increased V_P from 1920 m/s to 2705 m/s for the 40:60 blending ratio, and from 2360 m/s to 2891 m/s for the 80:20 blending ratio. The gradual rise in pulse velocity reflects enhanced material compaction, stronger bonding, and a more uniform internal structure as the coarser particle and cement content increase.

A clear increasing trend was observed in both P-wave velocity and constrained modulus across the blends Fig. 16, indicating enhanced stiffness and homogeneity in the FDR samples as the coarser proportion and cement content increased. This behavior aligns with previous research, which reports that UPV increases with improved matrix densification and reduced void content in cement-stabilized mixtures . Furthermore, a linear relationship was established between unconfined compressive strength (UCS) and P-wave velocity (Eq. 9), with a coefficient of determination (R^2= 0.709) Fig. 17. This suggests that UPV can serve as a reliable non-destructive predictor of UCS, as also observed in earlier studies involving cement-stabilized materials.

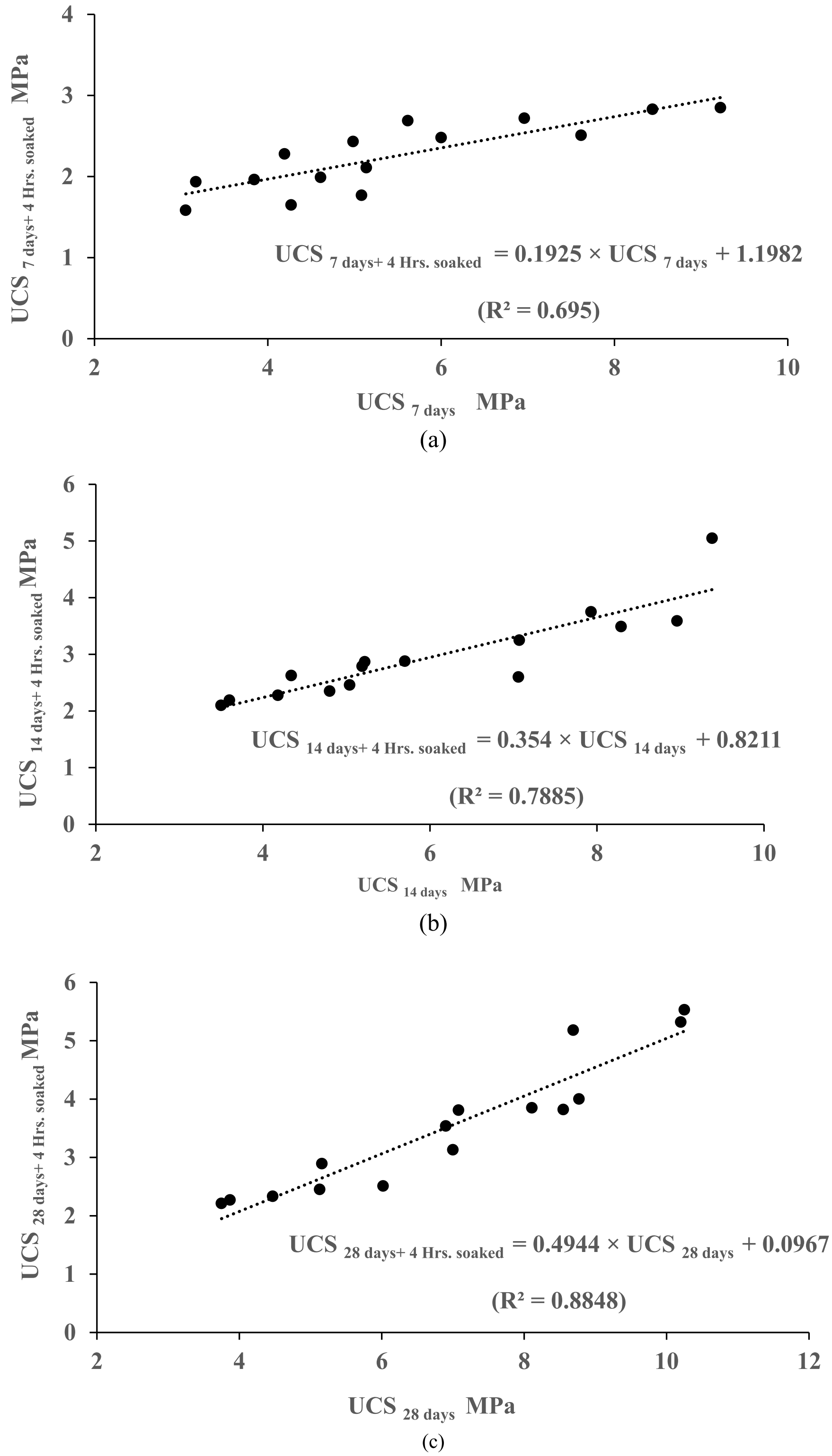


Fig. 13. Correlation between soaked and unsoaked UCS (a)$UCS_{7\ days}$ and $UCS_{7days+4Hrs.soaked}$, (b)$UCS_{14\ days}$ and $UCS_{14\ days+4Hrs.soaked}$, (c)$UCS_{28days}$ and $UCS_{28\ days+4Hrs.\ soaked}$.

3.7. Microstructural performance analysis

3.7.1. Scanning electron microscopy (SEM)

The internal structure of both untreated and cement stabilized FDR materials was studied using SEM. As shown in Fig. 18 The untreated sample revealed a loosely arranged granular structure with noticeable voids, indicating a weak and porous matrix due to the absence of cementitious bonds. In contrast, cement-stabilized specimens exhibited a much denser and more cohesive matrix with significantly reduced pore spaces, suggesting enhanced compaction and improved particle interlocking. The formation of amorphous, gel like hydration products, primarily calcium silicate hydrate (C-S-H), was clearly visible, confirming ongoing cement hydration. These products play a critical role in binding the particles and improving matrix strength. Additionally, the presence

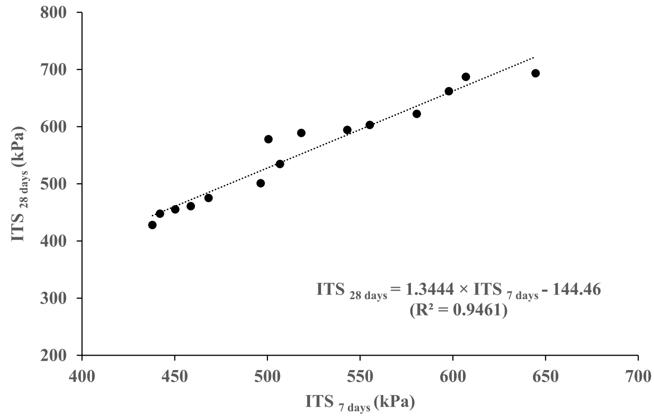


Fig. 14. Correlation between 7 and 28 days ITS values of FDR samples.

of calcite deposits and more extensive C-S-H coverage was observed in specimens with higher cement content, indicating supplementary carbonation and pozzolanic reactions. Importantly, the Fig. 19 illustrates no significant variation in microstructural features was observed across different blending proportions, indicating that gradation had no visible influence on the SEM morphology of the stabilized mixtures. This suggests that cement content and curing conditions play a more dominant role in microstructural development than aggregate gradation. Among all samples, the 70:30 blend with 5% cement after 28 days of curing refer to Fig. 20 showed the most compact, well bonded matrix, aligning with its superior strength results obtained from UCS and ITS tests.

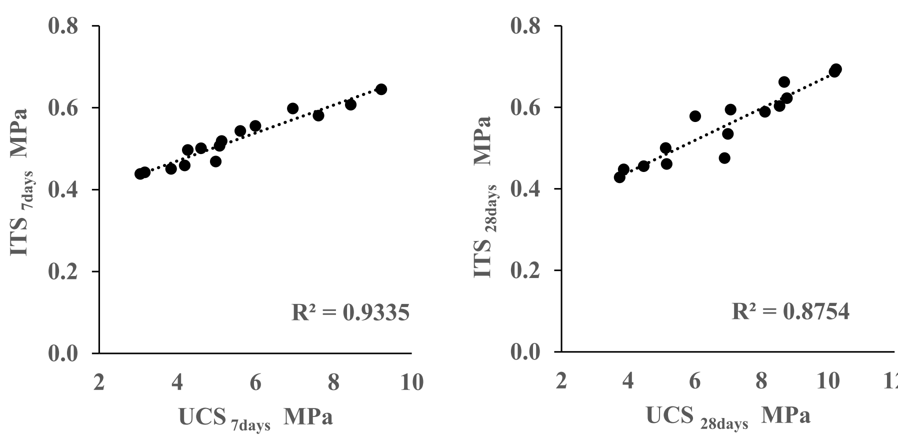
3.7.2. Energy dispersive X-ray spectroscopy (EDS)

The EDS spectra provided elemental composition data supporting the microstructural observations. Cement -stabilized samples exhibited prominent peaks for calcium (Ca), silicon (Si), oxygen (O), and aluminum (Al), all of which are associated with the formation of hydration products, particularly C-S-H and calcium aluminate hydrates. A higher Ca/Si ratio was observed in specimens with increased cement content, consistent with the dominant formation of C-S-H.

3.7.3. X-ray diffraction (XRD)

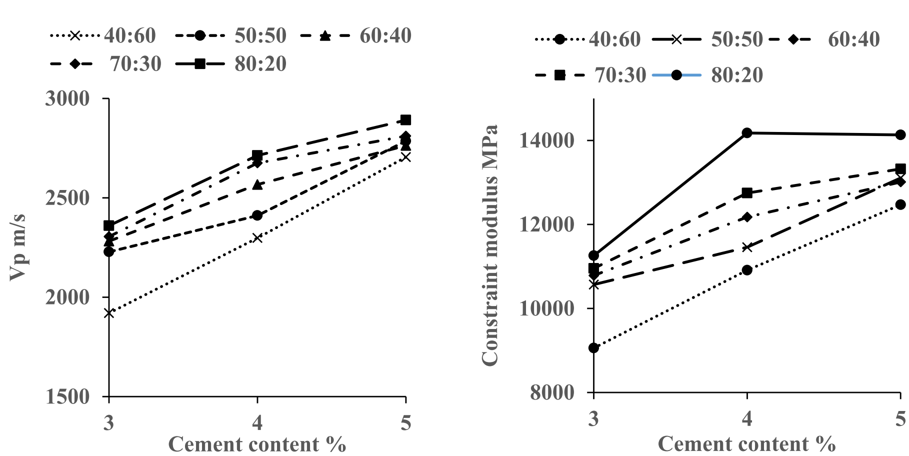
The X-ray diffraction (XRD) patterns of the untreated and cement-stabilized Full-Depth Reclamation (FDR) materials cured for 28 days are presented in Fig. 21. The analysis provides insight into the mineralogical transformations that occur due to cement stabilization and curing.

In contrast, the cement-stabilized specimens show significant changes in mineralogical composition. For the 3% cement-treated sample (70–30–3C–28 Day), new crystalline phases such as Alite (A) around 32° 2θ and calcite (C) at 29.4°, 36°, and 39° 2θ are observed alongside Quartz. The emergence of Alite (Ca_3SiO_5) demonstrates the incorporation of cementitious compounds, while the formation of



(a) (b)

Fig. 15. Correlation between UCS and ITS (a)7 days (b)28 days.



(a) (b)

Fig. 16. Effect of cement on (a)V_p and (b)constraint modulus of 28 days cured FDR mixes.

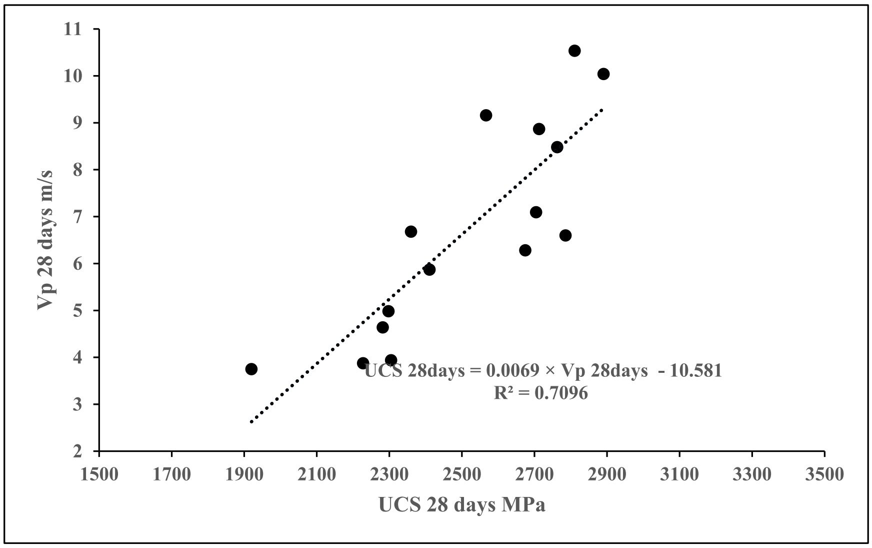


Fig. 17. Correlation between 28-day UCS and Vp.

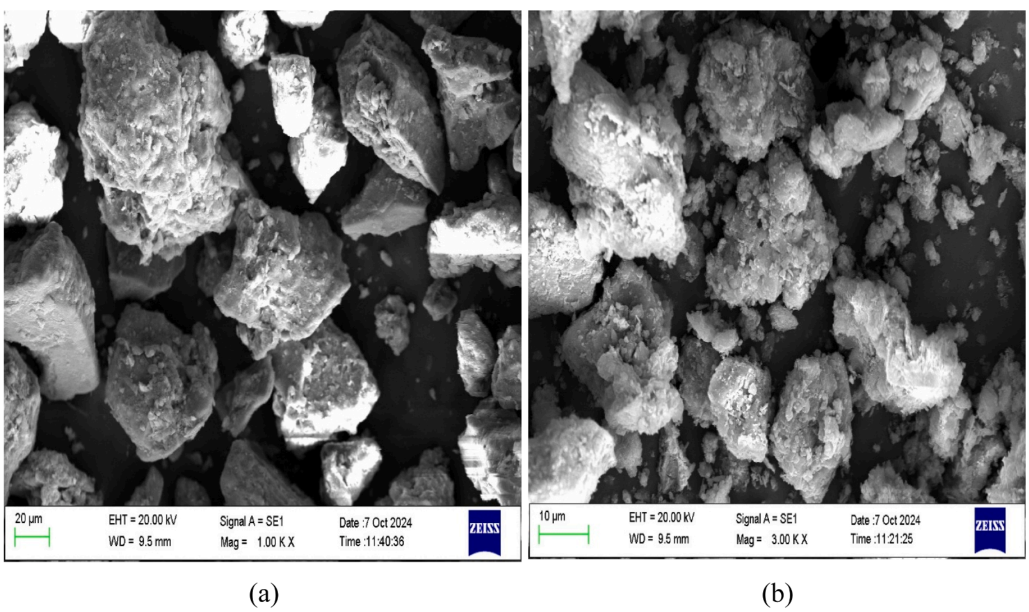


Fig. 18. SEM images of FDR material (a) unstabilized, (b) cement stabilizFig. 19 SEM images of cement stabilized FDR samples showing different blending proportions with 5% cement after 7 days of curing: (a) 40:60, (b) 50:50, (c) 60:40, (d) 70:30, (e) 80:20.

Calcite suggests carbonation of calcium hydroxide during curing.

With 4% cement addition (70–30–4C–28Day), the XRD pattern reveals enhanced intensities of Alite (A) and Calcite (C) peaks, along with traces of Muscovite (M). The strong Alite peak near 2θ ≈ 32° reflects higher degrees of hydration, leading to the formation of calcium silicate hydrate (C–S–H) gel, which contributes to strength gain. The pronounced Calcite peaks indicate secondary carbonation reactions, enhancing matrix densification and durability.

In the **70–30–5C–28Day** specimen, the peaks of **Muscovite** and **Calcite** are more prominent, while the Alite peaks are relatively reduced. This reduction indicates that a significant portion of Alite has been consumed during hydration, gradual formation of amorphous C–S–H and calcium hydroxide phases. The enhanced Calcite formation points toward the extensive carbonation of $Ca(OH)_2$, which aids in the development of a denser and more stable microstructure. This interpretation is further supported by Scanning Electron Microscopy (SEM), which revealed the development of a dense and cohesive matrix in Cement -stabilized samples, characterized by a gel like morphology typical of C-S-H.

4. Conclusions

A systematically designed laboratory investigation was conducted to evaluate the mechanical, microstructural, and nondestructive test performance of cement stabilized full depth reclaimed (FDR) base materials incorporating different coarse to fine aggregate blending proportions, cement contents, and curing periods. The aim was to assess the suitability of these mixes for use in the base layers of full depth reclaimed roads. The untreated FDR materials displayed inadequate strength characteristics, highlighting the necessity of cement stabilization. OPC-43 grade was employed as the primary stabilizing agent. Based on the test results and analytical findings, the major conclusions of this study are summarised below:

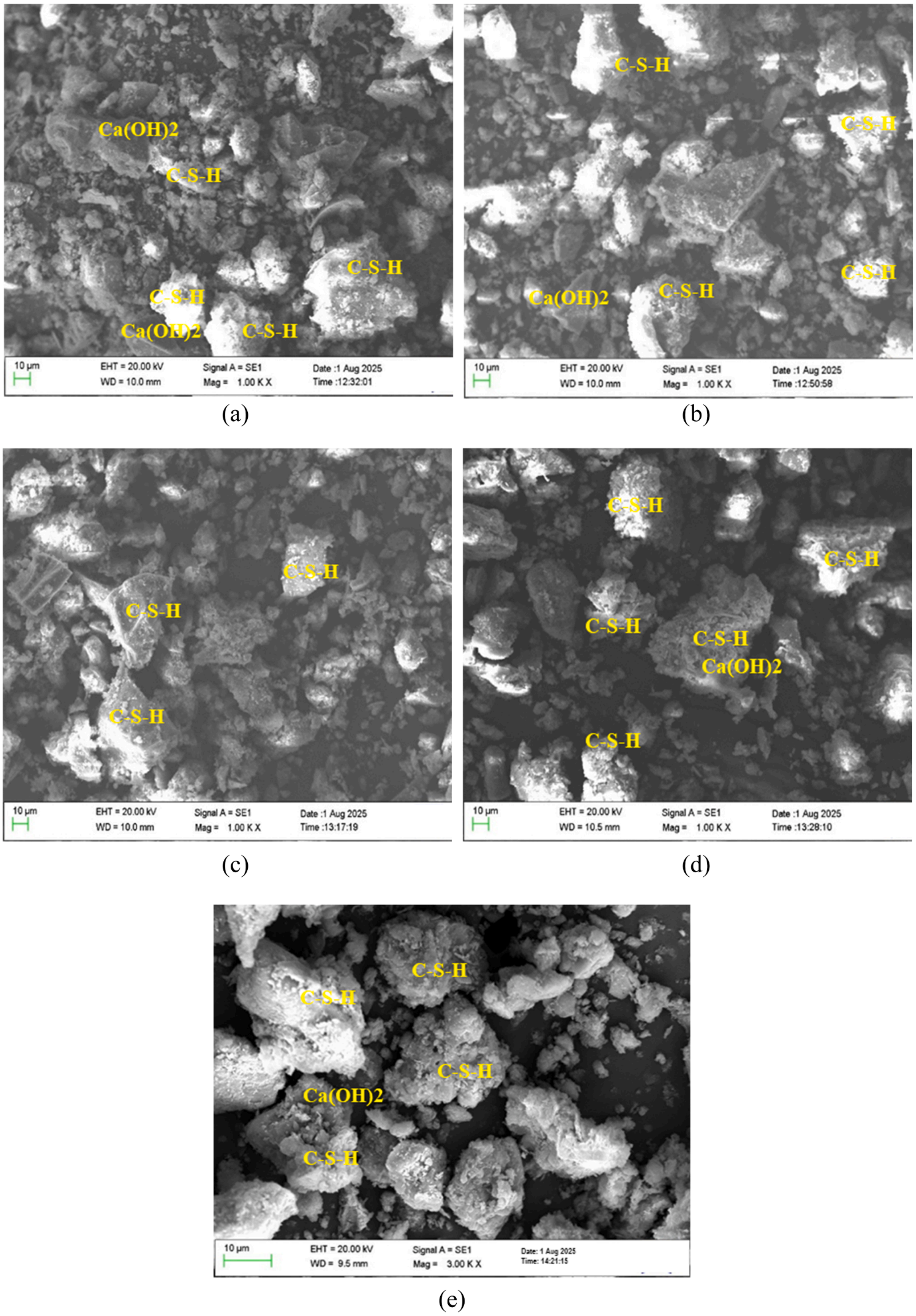


Fig. 19. SEM images of cement stabilizedFDR samples showing different blending proportions with 5% cement after 7 days of curing:(a) 40:60,(b) 50:50,(c) 60:40,(d) 70:30,(e) 80:20.

1. The untreated FDR materials exhibited unconfined compressive strength (UCS) values less than 1.5 MPa, which are inadequate for base layer applications, especially under soaked conditions. This confirms the necessity of cement stabilization.
2. Mechanical strength was strongly influenced by gradation, cement content, and curing durations. Optimized blends of 60:40, 70:30, and 80:20 with 4% –5% cement exceeded the IRC UCS criterion (4.95 MPa). The 70:30 mix performed best, achieving UCS greater than10 MPa, FS 1.17 MPa, and ITS 0.67 MPa after 28 days.
3. SEM and XRD analyses confirmed the transition from a loose granular structure to a dense matrix due to C-S-H gel formation, improved particle bonding, and reduced porosity. Cement content and curing duration were the dominant factors, with the 70:30 blend at 5% cement showing the most compact structure.
4. UPV results (1920–2891 m/s) increased with cement and aggregate content, showing a moderate correlation with UCS ($R^2 = 0.709$), indicating UPV as a viable nondestructive quality control tool.

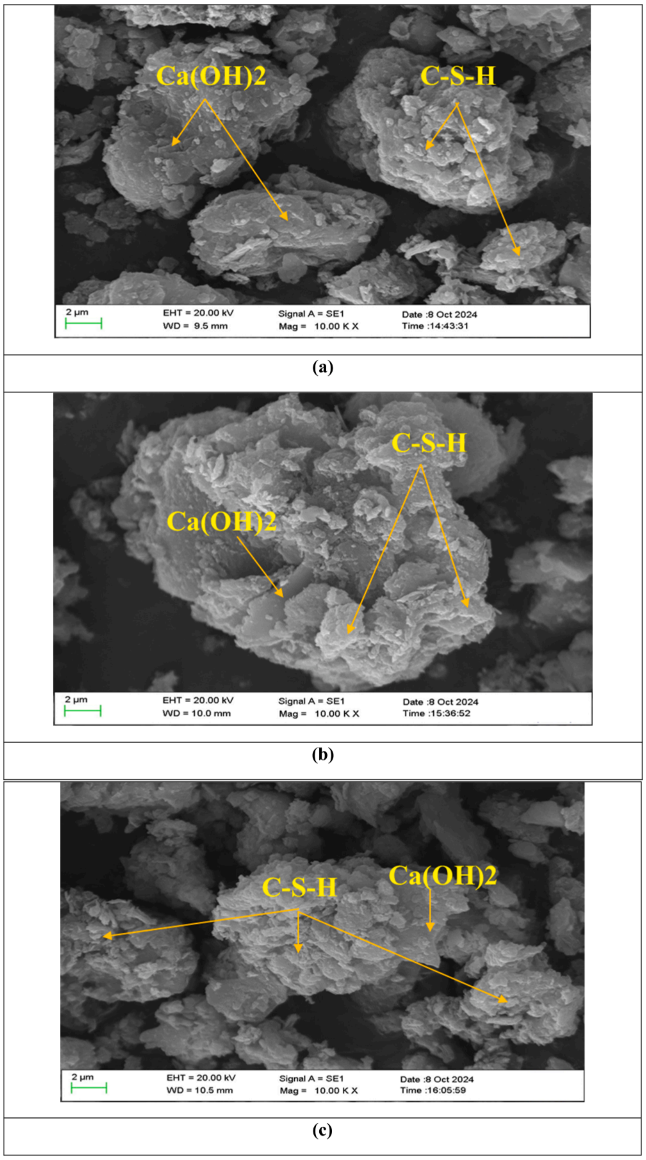


Fig. 20. SEM images of cement stabilized FDR samples with 70:30 blending proportion samples at different cement content: (a) 3%c, (b) 4%c, (c) 5%c.

5. Regression equations were developed to estimate UCS 28 d, ITS from UCS 7-day, soaked UCS from unsoaked UCS values, and UCS from UPV results.

Limitations of the study

The scope of this research was confined to reclaimed pavement material sourced from a single rural road, with stabilization carried out solely using OPC-43 grade. The laboratory controlled curing regime may not fully capture the variability of actual field environments, and the performance evaluation was limited to short-term curing periods of up to 28 days. Non-destructive assessment relied exclusively on ultrasonic pulse velocity (UPV), and microstructural investigations using SEM and XRD were performed on a restricted sample set. These constraints may affect the broader applicability of the results to other material types, binder options, and service conditions.

Future scope of the study

Future investigations could examine the performance of FDR mixtures incorporating various PI fines and alternative or blended binders, such as lime, fly ash, or slag, to improve both strength and sustainability. Long-term studies under diverse environmental exposures, including wet–dry and freeze–thaw cycles, would provide a more accurate prediction of in-service behavior. Incorporating additional non-destructive evaluation techniques alongside UPV and expanding microstructural analysis to a larger sample pool may yield more comprehensive insights. Field scale trials across varied geographic regions and traffic conditions are also recommended to validate laboratory results.

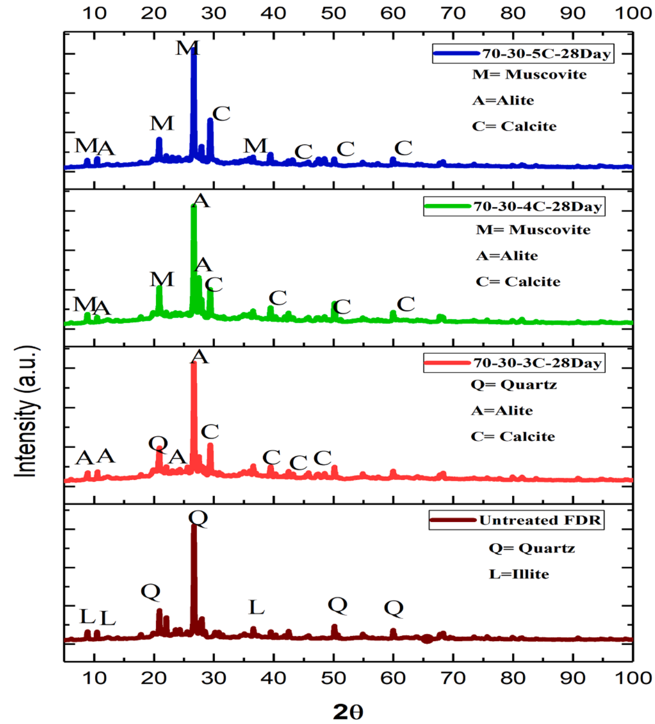


Fig. 21. XRD patterns for untreated and 70:30 blends stabilized with 3%, 4%, and 5% cement.

Data availability statement

All data, models, and code generated or used during the study will be made available upon request

CRediT authorship contribution statement

Jhunarani Ojha: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ankit Gupta:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Supriya Mohanty:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence that work reported in this paper.

Acknoledgement

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