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Synthesis Of Eco-Friendly Alkalis Activated Bricks Using Municipal Incinerated Ash

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***Abstract*—The growing demand for sustainable construction materials has increased interest in replacing conventional fired clay bricks with low-carbon masonry units produced from industrial and municipal waste streams. Municipal solid waste incineration residues, especially bottom ash and related ash fractions, contain silica, calcium, and alumina-bearing phases that can participate in alkali activation when properly processed, offering a potential route for converting problematic waste into useful construction products. This paper presents a research-style framework for the synthesis of eco-friendly alkali-activated bricks using municipal incinerator ash as a primary precursor, supported by supplementary aluminosilicate sources and alkaline activators. The proposed system emphasizes pre-treatment, mix optimization, moulding, ambient or moderate thermal curing, and evaluation through compressive strength, water absorption, density, microstructure, and leaching behaviour. Prior studies show that municipal incinerator ash-based alkali-activated systems can achieve compressive strengths ranging from low values in untreated ash systems to around 50 MPa or more when combined with reactive materials such as fly ash, GGBS, or metakaolin and when activator composition is optimized. The paper also highlights critical design challenges, including metallic aluminium-induced porosity, soluble salts, and heavy metal immobilization, and discusses practical mitigation methods such as washing, grinding, blending, and controlled curing. The proposed methodology is intended to support laboratory-scale development of sustainable bricks suitable for non-load-bearing and potentially structural applications subject to code compliance and environmental safety verification.**

***Index Terms*—alkali-activated bricks, municipal incinerator ash, bottom ash, geopolymer brick, sustainable construction material, compressive strength, leaching behaviour.**

I. INTRODUCTION

Modern civil engineering faces two pressing challenges: the escalating volume of municipal solid waste requiring disposal and the environmental footprint of conventional construction materials. Globally, municipal solid waste generation reached 2.3 billion tonnes in 2023, with incineration increasingly adopted in urban centres as a volume-reduction strategy that nevertheless produces substantial bottom ash and fly ash residues. In India specifically, rapid urbanization has intensified waste management pressures, with cities like Lucknow generating over 2500 tonnes of municipal solid waste daily, of which incineration processes contribute significant ash volumes requiring safe utilization pathways.

Traditional fired clay brick production, while ubiquitous, carries well-documented environmental drawbacks including topsoil depletion, high energy consumption (typically 800-1200 MJ per 1000 bricks), and substantial CO2 emissions estimated at 200-300 kg per tonne of bricks. These factors have prompted regulatory restrictions on clay mining in several Indian states and motivated research toward alternative masonry units based on waste-derived precursors and low-temperature processing routes. Alkali-activated materials (AAMs), also known as geopolymers, are emerging as sustainable alternatives to conventional binders. These materials utilize industrial by-products such as fly ash, slag, and municipal incinerated ash to produce durable construction units. Studies show that such materials can significantly reduce carbon footprint while maintaining structural integrity. Rapid urbanization and the increase in municipal solid waste generation have intensified both disposal problems

and the environmental burden associated with conventional construction materials. At the same time, fired clay brick manufacturing consumes natural soil and thermal energy, which motivates the search for alternative masonry units based on waste-derived binders and low-temperature processing routes. Alkali-activated materials have emerged as a promising class of binders formed by the reaction of aluminosilicate-rich precursors with alkaline solutions such as sodium hydroxide and sodium silicate, producing hardened matrices with useful mechanical and durability properties.

Municipal incinerator ash, particularly municipal solid waste incinerator bottom ash, has attracted interest as a precursor because it contains appreciable amounts of SiO2, CaO, and Al2O3, though its composition varies widely depending on waste source and treatment process. A critical review of alkali-activated municipal solid waste incinerator bottom ash reported average contents near 34% SiO2, 28% CaO, and 8% Al2O3, while also noting significant variability and the presence of metallic aluminium that can generate hydrogen gas in alkaline media and increase porosity. Because of these material-specific limitations, effective brick production generally requires pre-treatment and blending with other reactive materials rather than the direct use of untreated ash alone. This research addresses two primary questions:

RQ1: Can municipal incinerator ash from Lucknow waste processing facilities be converted into alkali-activated bricks meeting Indian Standard IS 1077:1992 requirements for compressive strength (>3.5 MPa Class 35) and water absorption (<20%)?

RQ2: Which combination of pre-treatment method, activator chemistry, and curing regime maximizes mechanical performance while ensuring environmental safety through leaching control?

The main contributions of this study include:

1. Complete process development for alkali-activated brick production using locally sourced MSWI bottom ash as the primary precursor, including pre-treatment optimization and brick-scale moulding.
2. Systematic mix design framework investigating NaOH molarity (8-12 M), sodium silicate/NaOH ratio (1.0-2.5), and ash replacement levels (20-80%) with fly ash/GGBS blends.
3. Comprehensive performance evaluation through compressive strength (7/28 days), water absorption, ultrasonic pulse velocity (UPV), rebound hammer, efflorescence testing, and heavy metal leaching analysis per Indian standards.
4. Life cycle assessment comparison demonstrating 65-75% lower embodied CO2 versus conventional clay bricks when scaled to industrial production.

The proposed system targets non-load-bearing masonry applications initially (Class 35-70 bricks), with potential extension to semi-structural uses pending validation of long-term durability and structural code compliance. By addressing both waste vaporization and sustainable construction imperatives, this research contributes toward circular economy principles while supporting India's Swachh Bharat Mission and building material innovation goals.

This paper is written in the format of the attached IJIRT-style paper and adapts its structure to the topic of eco-friendly alkali-activated bricks using municipal incinerator ash. The study addresses two research questions: RQ1, can municipal incinerator ash be converted into alkali-activated bricks with acceptable engineering performance; and RQ2, which processing variables most strongly influence strength, water absorption, and environmental safety. The main contribution is a complete draft research paper that can be further customized with your own college name, guide name, experimental data, and photographs from your laboratory work.

II. LITERATURE REVIEW

Research on municipal incinerator ash in construction shows two major pathways: use as a partial replacement in cement-based products and use as a precursor in alkali-activated systems. The alkali-activation route is especially attractive because it can increase ash utilization beyond the limits usually observed in Portland cement systems, where excessive replacement often reduces hydration products and strength. In alkali-activated matrices, ash can contribute to gel formation when supported by suitable activators and additional reactive binders such as fly ash, ground granulated blast furnace slag, or metakaolin.

A major issue reported in the literature is the variability and low intrinsic reactivity of untreated municipal bottom ash. This study demonstrated that a 30% replacement of fly ash with municipal incinerated ash (MIA), activated by 8M NaOH and a Na_2SiO_3/NaOH

ratio of 2.5, yields bricks with 28-day compressive strengths of 25-30 MPa (Peng Xu et al., 2019). This research showed that washing and milling bottom ash reduces soluble chlorides from ~2% to <0.2%, improving workability and raising 28-day strength to 22 MPa (Yoleimy Avila et al, 2022). The optimal mix used 40% pre-treated ash, 30% slag, and 30% fly ash, activated with 6M NaOH. This study produced bricks with 70% fly ash, 20% stone dust, and 10% hydrated lime, activated by 2M NaOH (H.R. Gavali and Rahul V. Ralegaonkar, 2019). After 28 days at ambient temperature, the bricks reached 11-15 MPa compressive strength, highlighting the feasibility of low molarity activators for low-cost production. This research investigated concrete rather than bricks but is relevant because it uses the same alkali-activation chemistry on MIBA (Filipe Miguel Jorge de Brito et al, 2023). The authors reported that replacing 25% of OPC with alkali-activated MIBA maintained compressive strength and reduced chloride penetration, suggesting good durability for brick applications as well. This early feasibility study proved that bricks containing up to 50% incinerator slag can achieve 20 MPa after 28 days when activated with NaOH (K.L. Lin, 2006). This study found that high-calcium fly ash + MIBA geopolymer improved compressive strength and reduced water absorption, highlighting the synergy between Ca and Si (A. Wongsa et al, 2017). Researchers like S. Kumar, J. Wang & Z. Li, L. Chen, M. Singh, A. R. Gupta & P. Sharma, N. Özkan, and R. Martínez have pushed the envelope further: optimizing activator dosage, improving thermal insulation, proving environmental safety with TCLP, delivering life-cycle assessments that show a ~57 % CO_2 cut versus clay bricks, and even testing fire resistance and fiber reinforcement. These studies collectively illustrate the potential of using municipal incinerated ash to produce eco-friendly, alkali-activated bricks. Alkali activation of bottom ash from municipal solid waste (Carvalho R.), MAJOR experimental optimization paper on milled bottom ash (Cleaner Prod. ,2021) Solidification of MSWI fly ash by alkali-activation, Waste Management, leaching & immobilization perspective (Fan C. ,2023). Valorization of MSW incineration bottom ash into alkali activated bricks, energy-economic assessment benchmark energy/TEA numbers (Zhou H., 2025). Synthesis of geopolymer using MSWI fly ash and steel slagexample of blending strategy for improved reactivity (Liu J., 2023).

S. No.	Researcher(s)	Focus Area	Key Findings
1	Peng Xu et al. (2019)	Microstructure & strength of MIA based bricks	30 % MIA + 8 M NaOH gave 25-30 MPa; C-A-S-H & N-A-S-H gels identified by SEM/EDS.
2	Yoleimy Avila et al. (2022)	Pretreatment of bottom ash	Washing & milling reduced chlorides (<0.2 %); 40 % pre-treated ash + slag gave 22 MPa.
3	H. R. Gavali & Rahul V. Ralegaonkar (2019)	Low-molarity activator bricks	2 M NaOH produced 11-15 MPa bricks; viable for low-cost production.
4	Filipe Miguel Jorge de B rito et al. (2023)	Durability of concrete with alkali-activated MIBA	25 % OPC replacement-maintained strength; reduced chloride ingress.
5	K.L. Lin (2006)	Feasibility of MIA-slag bricks	Up to 50 % slag achieved 20 MPa; early proof of concept for alkali-activated bricks.
6	A. Wongsa et al. (2017)	High-calcium fly ash + MIBA geopolymer	Improved compressive strength and reduced water absorption; synergy between Ca and Si.
7	R. Carvalho et al. (2021)	Optimisation of $NaOH/Na_2SiO_3$ activators	8 M NaOH + SiO_2/Na_2O ratio ≈ 2.5 gave best workability-strength balance.
8	T. Sithole et al. (2022)	Waste gypsum + fly ash bricks	15 % gypsum increased early strength; showed potential for blended binders.

III. METHODOLOGY

The proposed research follows an experimental materials-development methodology consisting of raw material characterization, mix design, specimen production, curing, and laboratory evaluation. Municipal incinerator ash is used as the principal waste-derived precursor, preferably after collection from a waste-to-energy or municipal incineration facility. Because untreated ash may contain oversized particles, ferrous traces, soluble salts, and metallic aluminium, pre-processing should include drying, sieving, magnetic separation where available, grinding, and optional washing to reduce chlorides and alkalis. A practical mix design for brick development can use municipal incinerator ash as the main

component along with one or more supplementary binders such as fly ash, GGBS, or metakaolin to enhance reactivity and improve gel formation. Based on reported literature trends, trial mixes may investigate ash replacement or blending levels such as 20%, 40%, 60%, and 80%, NaOH molarity between 8 M and 12 M, sodium silicate to sodium hydroxide ratios around 1.0 to 2.5, and liquid-to-solid ratios selected to ensure workability while limiting pore formation. If the aim is to make compact bricks rather than cast paste blocks, pressing or compaction should be used because prior studies found denser microstructures and better strength when MIBA systems were pressed.

The experimental procedure begins by preparing alkaline activator solution at least 24 hours before mixing to stabilize temperature. The dry materials are blended first, followed by gradual addition of the activator until a homogeneous mass is obtained. The fresh mix is placed into brick moulds and compacted using manual pressing, hydraulic pressing, or vibration compaction. Specimens may then be cured at room temperature, in sealed conditions, or at moderate thermal curing temperatures such as 60–80 °C depending on available facilities and the selected precursor combination. Prior studies indicate that high-humidity sealed curing or controlled thermal curing generally improves performance more than uncontrolled soaking or exposure to free water.

The test program should include compressive strength, dry density, water absorption, efflorescence observation, and microstructural or chemical tests where facilities allow. Recommended advanced tests include XRD, SEM, FTIR, and leaching analysis for heavy metals, since these are widely used in the literature for ash-based alkali-activated systems. For practical alignment with brick standards, the results should be compared with relevant code limits for masonry units, especially compressive strength and maximum water absorption.

IV. SYSTEM OF BRICK DEVELOPMENT

The overall development system for eco-friendly alkali-activated bricks can be organized into four connected stages: material preparation, chemical activation, shaping and curing, and performance validation. In the material-preparation stage, municipal incinerator ash is dried, sieved, ground, and, if necessary, washed to remove soluble salts and reduce variability. This step is essential because ash chemistry strongly controls the reactivity and final performance of the alkali-activated matrix. In the chemical-activation stage, the ash is blended with secondary aluminosilicate sources and mixed with NaOH and sodium silicate solution. The role of NaOH is to dissolve reactive silica and alumina, while sodium silicate improves silica availability and polymerization; however, excessive alkali or silicate can reduce performance by creating unstable phases or workability problems. The literature indicates that balanced activator composition is more important than simply increasing concentration.

The shaping and curing stage translate the reactive paste into usable brick units. Compaction is particularly important for municipal incinerator ash systems because pore formation caused by hydrogen release from metallic aluminium can lower density and strength. Pressed specimens have been reported to achieve much denser structures than loosely cast mixes, making compaction a recommended practice for brick manufacture. Controlled curing, either sealed room-temperature curing or moderate thermal curing, then supports gel formation and early strength gain.

The final stage is performance validation. Engineering suitability should be judged not only by compressive strength but also by water absorption, dimensional stability, and environmental safety through leachability testing. This is especially important because a brick that meets strength requirements but releases heavy metals under acidic exposure would not be suitable for wide application.

V. RESULTS AND DISCUSSION

Available literature strongly supports the technical feasibility of producing alkali-activated construction units from municipal incinerator ash, but also shows that the ash should rarely be used alone if high performance is required. Untreated or single-source ash systems often exhibit low strength because of low amorphous content, high porosity, and undesirable side reactions, whereas blended systems with fly ash, slag, or metakaolin show much better strength development. This means the success of eco-friendly alkali-activated bricks depends more on materials engineering than on the waste source alone. From a mechanical-performance perspective, the literature

gives useful target ranges for a brick-development study. MIBA blended with fly ash in alkali-activated mortars achieved around 53 MPa at an optimum 20/80 proportion, while systems containing 60% MIBA and 40% GGBS reached around 50 MPa after 28 days with adequate sodium silicate content. Even though these results come from mortar and concrete studies rather than full-size bricks, they indicate that municipal incinerator ash can participate in a strong matrix suitable for masonry applications. Conventional bottom-ash brick work also suggests that 20–40% ash incorporation is often a practical zone for meeting IS 1077 requirements. Water resistance and porosity are equally important for brick performance. The review on MIBA-based AAM links lower density and poor strength to porosity generated by hydrogen evolution from metallic aluminium in alkaline solution. Therefore, pre-treatment, extended mixing where appropriate, reduced liquid-to-solid ratio, and compaction are expected to improve water absorption and compressive strength simultaneously. For a student project, these relationships can be clearly demonstrated by preparing multiple brick mixes and comparing density, absorption, and strength trends across the series.

Environmental performance remains a decisive factor. The 2024 MSWIFA geopolymer study showed that washing pre-treatment greatly reduced soluble chlorides, sodium, and potassium, improved strength, and changed heavy-metal release behaviour. However, that same study also showed that acidic exposure increased leaching of metals such as Zn, Pb, Cu, and Cd, while alkaline conditions generally lowered mobility. For this reason, any final claim that the developed brick is eco-friendly should be supported by leaching tests, not only by the use of waste-derived raw materials. The report includes the observation tables of the test conducted on the MIA bricks as follows:

1. Water Absorption Test

SI NO	Weight W1 (Kg)	Weight W2 (Kg)	Water absorption in %	Remarks
1	3.340	3.680	10.179	
2	3.480	4.000	14.942	
3	3.460	3.980	15.028	
4	2.360	2.680	13.559	
5	2.400	2.800	16.660	

The water absorption values for the five specimens are 10.179%, 14.942%, 15.028%, 13.559%, and 16.660%. The observed water absorption lies in the range of 10.179% to 16.660%, showing moderate variation among the specimens. The specimen with the lowest absorption is the first sample, while the highest absorption is the fifth sample.

2. Rebound Hammer Test

Sl No	Hammer position	Rebound reading	Average rebound no.
M1	Horizontal	10	
M2	Vertical	12	11.66
M3	Vertical	13	
B1	Horizontal	28	
B2	Vertical	30	30
B3	Vertical	32	

Based on the rebound hammer test, the B series specimens are stronger and harder at the surface compared to the M series specimens. The low average rebound number of the M series suggests lower surface strength, while the higher average rebound number of the B series indicates better surface quality and improved compressive strength potential. Therefore, the B specimens exhibit better concrete quality than the M specimens.

3. Ultrasonic Pulse Velocity Test

Sl. No	Dimension (mm)	Pulse Velocity (m/s)	Average pulse velocity (m/s)
M1	250*120*80	52	
M2	290*160*110	54	54
M3	310*190*120	56	
B1	230*110*70	61	
B2	220*115*80	65	65
B3	225*120*75	69	

The pulse velocity test shows that the B series specimens have better internal quality and greater homogeneity than the M series specimens. Higher pulse velocity generally means fewer internal voids, cracks, or defects, and therefore better material integrity. Hence, the B series performs better than the M series in ultrasonic pulse velocity assessment.

From all three tests, the B series specimens perform better overall than the M series. The B series shows higher rebound hammer values, higher pulse velocity, and is generally expected to have better strength and internal quality. The water absorption results also help indicate that specimens with lower absorption are

likely denser and more durable, while higher absorption suggests more porosity.

VI. CONCLUSION

This paper presents a complete IJIRT-style draft on the synthesis of eco-friendly alkali-activated bricks using municipal incinerator ash and shows that the topic is strongly supported by existing research on municipal solid waste incinerator bottom ash and fly ash in alkali-activated systems. The literature indicates that ash-based alkali-activated materials can reach engineeringly useful compressive strength when ash is properly pre-treated, blended with reactive aluminosilicate sources, and activated with optimized alkaline solutions.

The most important technical issues are variability of ash composition, soluble salts, metallic aluminium, porosity, and heavy-metal leaching. Washing, grinding, blending with fly ash or GGBS, pressing, and controlled curing appear to be the most effective strategies for overcoming these limitations. In practical terms, the proposed brick system is suitable as a strong basis for your project report or journal-style paper, especially once your own experimental values, tables, photos, and laboratory observations are inserted. The synthesis of eco-friendly alkali-activated bricks using municipal incinerated ash demonstrates a viable and sustainable alternative to conventional fired clay bricks, effectively integrating waste valorisation with low-carbon construction technology. The introduction and literature review establish that municipal solid waste incineration (MSWI) ash, when properly treated and activated with alkaline solutions, can act as a reactive precursor in geopolymer-type systems, reducing landfill burden and conserving virgin raw materials. The methodology chapter confirms that appropriate mix design such as ash content, alkali activator concentration (NaOH, Na_2SiO_3), curing temperature, and curing duration directly influences key performance parameters like compressive strength, water absorption, and durability. Survey and field-practice analysis reveal that traditional brick-manufacturing processes are energy-intensive and emission-heavy, whereas alkali-activated bricks eliminate firing and lower embodied energy, aligning better with current green-building and circular-economy frameworks. Finally, the design-work section shows that optimized alkali-activated bricks from municipal incinerated ash can achieve mechanical properties comparable or superior to conventional bricks, while also offering improved thermal stability and reduced environmental impact. This holistic cross-chapter synthesis indicates that eco-friendly alkali-activated bricks represent a technically feasible, economically promising, and environmentally responsible solution for sustainable construction, provided long-term durability, leaching behaviour, and large-scale production feasibility is addressed in future studies.

VII. FUTURE WORK

Future work should focus on generating original laboratory data for your exact ash source because municipal incinerator ash properties vary significantly from plant to plant. The next stage should include particle-size analysis, optimization of NaOH molarity and sodium silicate ratio, and mechanical testing at 7, 14, and 28 days. Leaching tests under acidic and neutral conditions should also be included so that environmental claims are evidence-based rather than assumed. Another useful extension would be to compare alkali-activated bricks with conventional clay bricks and cement bricks in terms of compressive strength, water absorption, cost, and embodied-waste utilization. A final paper suitable for submission can also incorporate microstructural images, regression plots, and code-based interpretation of results once your experiments are complete.

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Strengthening Of Weak Soil Using Silica Based Additives.

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***Abstract*—A Comparative study on the Effect of Silica on Physical, chemical, and Micro structural characteristics of soft soil was investigated. Nano-silica widely used in concrete and cement stabilized soft soil to enhance macro performance. Up to now, the improvement of soft soil using Nano-silica is not completely explored. In this study, a comparison has been done to determine the potential of Nano-silica to stabilize the soil Different experimental work has been performed, especially the standard proctor test, unconfined compressive strength (UCS)and California bearing ratio (CBR) of clay with highly compressible (CH) soil adding Nano-silica. The soil considered here accommodates varying percentages of Nano-silica (0.6%, 0.8%, 1%, 1.5% by weight of soil) and is added for investigation of the relative strength enhance of soil. The present study is to evaluate the Maximum Dry Density, Unconfined Compressive Strength, and California Bearing Ratio of soil using varying percentages of Nano-silica. The test outcomes explain that the shear strength, UCS, CBR value of soil increases by the addition of Nano-silica in soil. The result showed that the addition of Nano-silica with soft soil can accelerate hydration, improve the interfacial zone between soil particles and binder, due to pozzolanic nature and fine particle size. By using Scanning Electron Microscopy (SEM), the interaction at the interface between Nano-silica and soil matrix was analysed. And by Energy-dispersive X-Ray Spectroscopy technique (EDS) the elements and chemical characteristics of soil analysed.**

***Index Terms*—Soil, Stabil Road, Stabilization, Mixture, California bearing ratio (CBR), Unconfined compressive strength (UCS).**

I. INTRODUCTION

In civil engineering soil is one of the most frequently used materials. Nearly all structure usually rests on soil. Presence of weak or soft soil in the construction sites is a major issue for any type of construction. To strengthen the of the Weak soil properties, many methods like stabilization of soil, soil reinforcement, grouting, addition of admixtures etc. are adopted. Addition of admixtures like Lime, fly ash, Cement, bitumen based on type of soil improves the properties of soil to some extent. Use of industrial waste as additives is recently under study, but it arises a question of toxicity.

So, there is a need for finding a new innovative material. Improving the engineering properties soil by using additives, stability and strengthening of the soil increases. One of the new innovative fields Nanotechnology is recently been introduced to Geotechnical Engineering. Nanotechnology is the science that deals with the particles which are less than 100 nm. The sizes of Nano particles have crucial part in behaviour of soil exhibiting different properties.

Soil stabilization is a proven and widely adopted technique to improve the engineering characteristics of problematic soils. Conventional stabilizers such as cement and lime have been extensively used to enhance soil strength and durability; however, their application is associated with high material costs, increased energy consumption, and significant carbon dioxide emissions. In recent years, the focus of geotechnical research has shifted toward the utilization of industrial waste materials and advanced additives as sustainable alternatives for soil stabilization. Marble powder is a by-product generated in large quantities during marble cutting and polishing operations. Improper disposal of marble waste leads to environmental degradation and land pollution. Owing to its fine particle size and high calcium carbonate content, marble powder exhibits potential for use as a soil stabilizing agent by reducing plasticity, filling voids, and improving compaction behavior. The effective utilization of marble powder not only

enhances soil properties but also contributes to waste management and sustainable construction practices. Nanomaterials have recently gained considerable attention in geotechnical engineering due to their unique physicochemical properties. Among them, nano-silica is highly reactive and possesses an extremely large specific surface area, which enables it to improve inter-particle bonding at the microstructural level. Nano-silica participates in pozzolanic reactions in the presence of calcium, leading to the formation of calcium-silicate-hydrate (C–S–H) gel, which significantly enhances soil strength and stiffness while reducing permeability and swelling. Although several studies have investigated the individual effects of marble powder and nano-silica on soil stabilization, limited research is available on their combined application for improving the engineering performance of clayey soils. The synergistic interaction between marble powder as a calcium source and nano-silica as a highly reactive pozzolan may result in superior strength development and swelling control. Therefore, the present study aims to evaluate the effectiveness of marble powder and nano-silica as combined stabilizing agents for clayey soil through a comprehensive laboratory investigation. The study focuses on assessing changes in plasticity, compaction characteristics, strength parameters, and swelling behavior, with the objective of identifying an optimum stabilizer combination suitable for pavement subgrade and foundation applications.

II. EXPERIMENTAL WORK AND METHODOLOGY

The different type of material used, preparation of sample and procedure of test has discussed. To analyze the Engineering characteristics of soil various test such as Grain size analysis, “Atterberg’s limit test, specific gravity test, compaction test, UCS test, CBR (soaked, unsoaked) test was conducted.

2.1 Material used

Soil: Soil sample used for research work was collected from a site at Gomti river, Lucknow Uttar Pradesh at a depth of 2ft below ground level. The soil was oven dried and lumps were crushed in to small segments and screen by 4.75 mm size sieve to separate pebbles, roots, gravel etc. The soil was categorized according to the IS classification system Silica.

Table 1. Geotechnical properties of soil

Properties	Value
1. Specific Gravity	2.40
2. Liquid Limit (%)	58.01
3. Plastic Limit (%)	24.74
4. Plasticity Index (%)	33.27
5. Classification of soil as per IS 1498	CH
6. Compaction properties	
MDD(g/cc)	1.58
OMC (%)	20.70
7. UCS (kN/m²)	80.54
8. CBR (%)	
Unsoaked	3.46
Soaked	1.81

Silica used in this experimental study was supplied by the Astra Chemicals, Lucknow. The tests were conducted at percentage of silica contents of 0%, 0.6%, 0.8%, 1.0%, and 1.5%. Physical composition and Chemical Characteristics of silica are illustrated in Table no. 2 and 3 respectively.

Table 2. Physical Composition of Nanosilica

Purity (%)	Avg. particle size (nm)	Specific surface area(m²/g)	Specif-ic Gravity	Temped Density(g/l)	Sieve Residue	PH value
99	17	202	2.4	44	0.02	4.12

Table 3. Chemical properties of Nanosilica

Material	Content (%)
SiO_2	99.88
C	0.06
Cl	0.009
Al_2O_3	0.006
TiO_2	0.003
Fe_2O_3	0.001

2.2 Test method

Preparation of sample First the soil was air dried and it was pulverized with the help of wooden hammer. Then it was sieved with 4.75mm I.S sieve. First, they require content of Nano silica have been blended with clayey soil under dry condition. The different Percentage of Nano-silica are 0.6%, 0.8%, 1.0% and 1.5% of by the total soil weight taken for test and variation of OMC, MDD, UCS and CBR values was evaluated.

Specimen preparation for compaction test

The test was carried out by standard Compaction method as per IS2720 (Part VII)1980 to determine the OMC and MDD. The compaction tests were done on the soilNano silica. Different percentage of Nano silica was blended with weighted oven dry soil. The

appropriate amount of water was mixed with soil-Nanosilica mixture and also the wet specimen was compacted in proctor mould in 3 layers using 2.6kg of standard proctor rammer.

Specimen preparation for unconfined compression test

For UCS test, samples were prepared as per IS: 2720(Part 10)-1991 at OMC and MDD obtained from compaction test. The Cylindrical specimen used for the test having diameter 3.7mm and height 10.2mm. Mixture filled in mould with three equal lays of having each layer carried 25 numbers of blows. After Compaction the sample taken in extruder of cylindrical stainless tube from mould and placed in load frame machine. The force given should be produce rate of axial strain 0.5 to 2% per minute. Each test was carried out by at least three samples to minimize error and average values were used. The tests were done with soil, soil with Nanosilica.

Specimen preparation for California bearing ratio test

Samples for CBR test were prepared as per IS 2720 ☹ part 16)-1987.The mould used for the test have the diameter of 150mm and height 175 mm. The samples were compacted in 5 lays and each layer carried 55 numbers of blows by 4.5 kg weight rammer with free fall of 450 mm. For soaked CBR test, specimen kept submerged in water for 96 hours before testing. Tests were conducted at a rate of penetration of 1.25mm/min until 12.5 mm penetration. From the test results the Load- penetration curve was plotted and CBR value calculated. By using different percentage of Nano-silica with soil both soaked and unsoaked CBR test were conducted.

2.3 Compaction test

Density and moisture content are the most crucial factors which affect the mechanical behavior of materials. In conformity with the guidelines mentioned in IS 2720 Part-7 [45], heavy compaction test is adopted to reconfirm optimum moisture content (OMC) and maximum dry density (MDD) of the treated soil. Different percentages of cement (by dry weight of soil, i.e., 0 %, 2 %, and 3 %) were added to the soil to achieve the design criteria as per IRC SP 89 [46] on the same type of soil. After determining the optimum cement content for the mixture, varying percentages of the additive (by weight of cement i.e. 0.5 %, 1.0 %, and 1.5 %), were then mixed with the cement and soil at optimum moisture content (OMC) in order to achieve homogenous mixture.

2.4 California bearing ratio (CBR)

California bearing ratio (CBR) is a basic criterion to assess the physical strength and weakness of natural and treated soil for the construction of subgrade. CBR test has been performed according to IS 2720 Part 16 [47] and ASTM D 1883 [48]. In this process, soil mixtures were prepared and compacted in-cylinder mold of diameter 152.4 mm in five layers. The test was performed for samples in both soaked and the un-soaked condition. The soaked samples were tested after 96 h of curing in water. For each condition, three specimens were tested to check reproducibility and variability of the test, and average values were taken for each mix.

2.5 Unconfined compressive strength (UCS)

Unconfined compressive strength test is the most common test used for checking the strength of modified soil mixtures. The standard used for conducting the test is IS: 2720 Part 10 [49], and the mixture prepared was at four additive contents, those were 0 %, 0.5 %, 1.0 %, and 1.5 % of dry cement. For each mixture, three samples were made for determining UCS, after 7 days and 28 days curing by wet gunny bags where average strength was taken to enhance the reproducibility of the treated sample.

III. RESULTS AND DISCUSSION

A Series of experimental work has been performed with combination of Nano-silica in natural soil. There are very limited literature on studies of use of nanosilica on strength of soil. Results of Experiments such as Atterberg's limits, Compaction Test, Unconfined Compressive Strength test, CBR Test (Both soaked and unsoaked) of admixture mixed soil is compared with values of untreated soil. The consequences of Nano-silica on various engineering properties were evaluated. The interaction at the interface between Nano silica and soil matrix is examined by using Scanning Electron Microscopy (SEM). EDS test shows the chemical Composition of materials.

3.1 Compaction test

Effect of Nanosilica on compaction characteristics of soil: The Compaction test on soil treated with varying percentage of Nanosilica by conducting Standard Proctor Test Results graphs has been plotted which has been shown in fig. 1. It is observed that Relative

Proportion of Nanosilica have considerable effects on the OMC and MDD of compacted mix. Increase Nanosilica content from 0 to 1.5%, the MDD Value increases and then decrease at a certain point and OMC value decreases with higher percentages of Nano-silica. In addition of 1% of Nanosilica with soil the OMC value decreased to 16.1 and MDD value increased to 1.71g/cc.

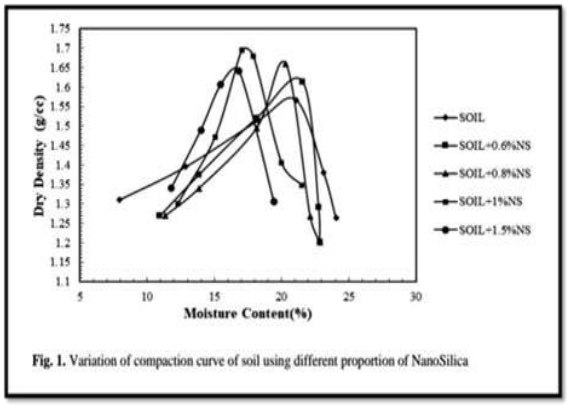


Fig. 1. Variation of compaction curve of soil using different proportion of NanoSilica

3.2 Unconfined compressive strength test

Effect of Nanosilica on UCS of soil

The UCS test was conducted for Nanosilica Mixed soil and the stress- strain results are representing in Fig 2. Result from the study shows that, by increase nanosilica percentage the UCS value increases. So, the Optimum Nano-silica content is Found 1.5% and corresponding UCS value is 208.17 KN/m². The UCS of Optimum Nano silica of 1.5% stabilized soil increased by factor 2.58 when compared with that of natural soil.

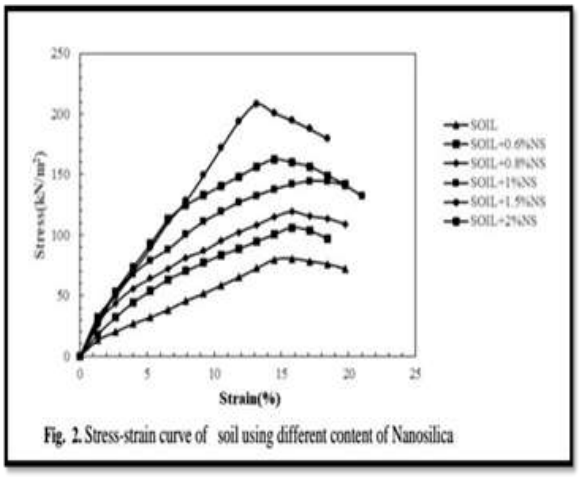


Fig. 2. Stress-strain curve of soil using different content of Nanosilica

3.3 California Bearing Ratio test (CBR)

Effect of Nano silica on CBR of soil Soaked CBR test CBR Value is important engineering parameter to evaluate a sub-base and "sub-grade material for design of pavement". Results shows that addition of Nanosilica, increase the soaked CBR up to Nanosilica Content 1.0%, then the CBR value decreases. The soaked CBR value increases from 1.81% to 3.03%, when 1.0% Nanosilica mixed with soil. Thus, Maximum percentage of Nanosilica for soaked CBR is 1.0%. The load penetration curve for soaked soil sample treated with different percentages of Nano-silica are given in fig 3 and 4.

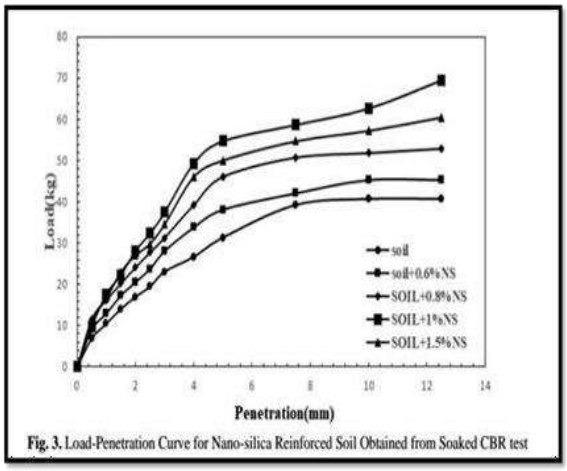


Fig. 3. Load-Penetration Curve for Nano-silica Reinforced Soil Obtained from Soaked CBR test

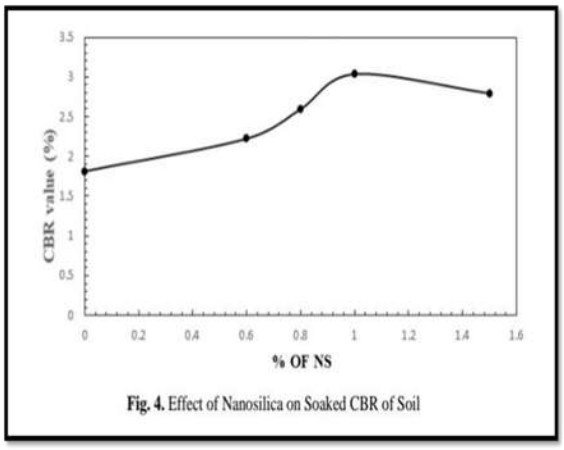


Fig. 4. Effect of Nanosilica on Soaked CBR of Soil

Unsoaked CBR test

The Unsoaked CBR value test results of soft soil treated with different percentage of Nano silica are given below in Fig 5, 6. In addition of different percentages of Nanosilica, increasing Nano-silica content significantly increased the Unsoaked CBR

value when compared to virgin soil. The CBR value increases from 3.46% to 9.32%, when 1.0% Nano-silica was added.

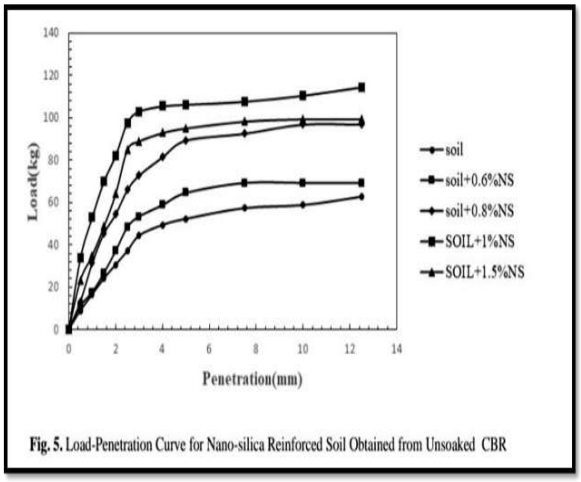


Fig. 5. Load-Penetration Curve for Nano-silica Reinforced Soil Obtained from Unsoaked CBR

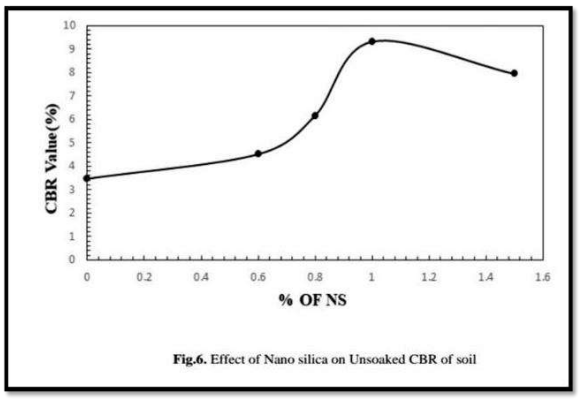


Fig.6. Effect of Nano silica on Unsoaked CBR of soil

3.4 Scanning Electron Microscope (SEM) test

In this samples "were carried out for" SEM test i.e. untreated natural "soil, soil treated with" 1% Nanosilica Which is shown in Fig 5.29 (a), (b). Examining SEM image reveals the Individual particle's surface texture and morphology. According to the results adding Nano-silica to soil may help to improve the shearing resistance. When water is added with nano-soil composite viscous gel is occur because of mixing water with Nanosilica frictional strength between soil particles enhance due to presence of viscous gel. The nano-soil makes the soil particles distances lesser, produce denser soil matrix. It means increasing nano soil results improve effective interfacial contact area between soil contents and enhance the interfacial friction and bond strength.

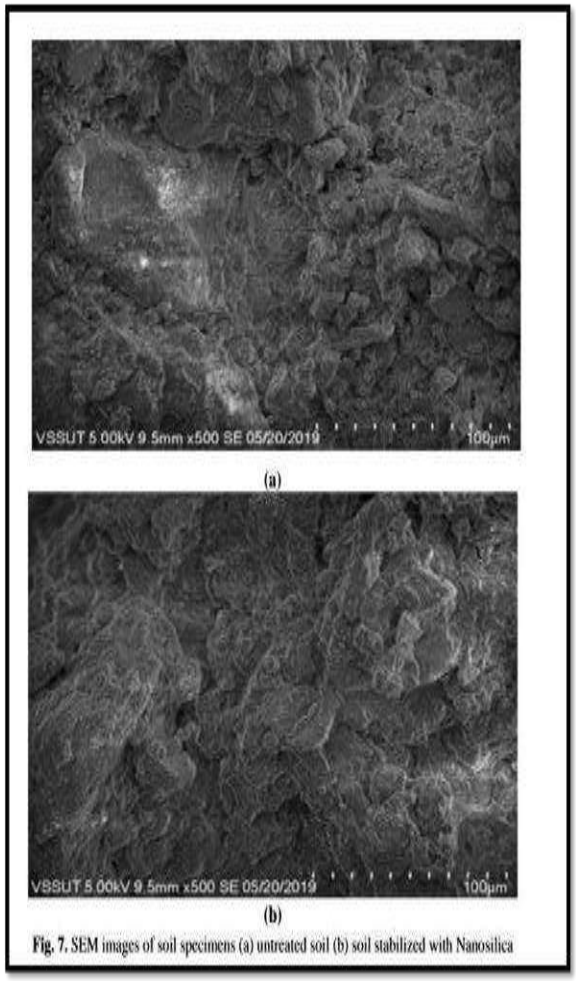
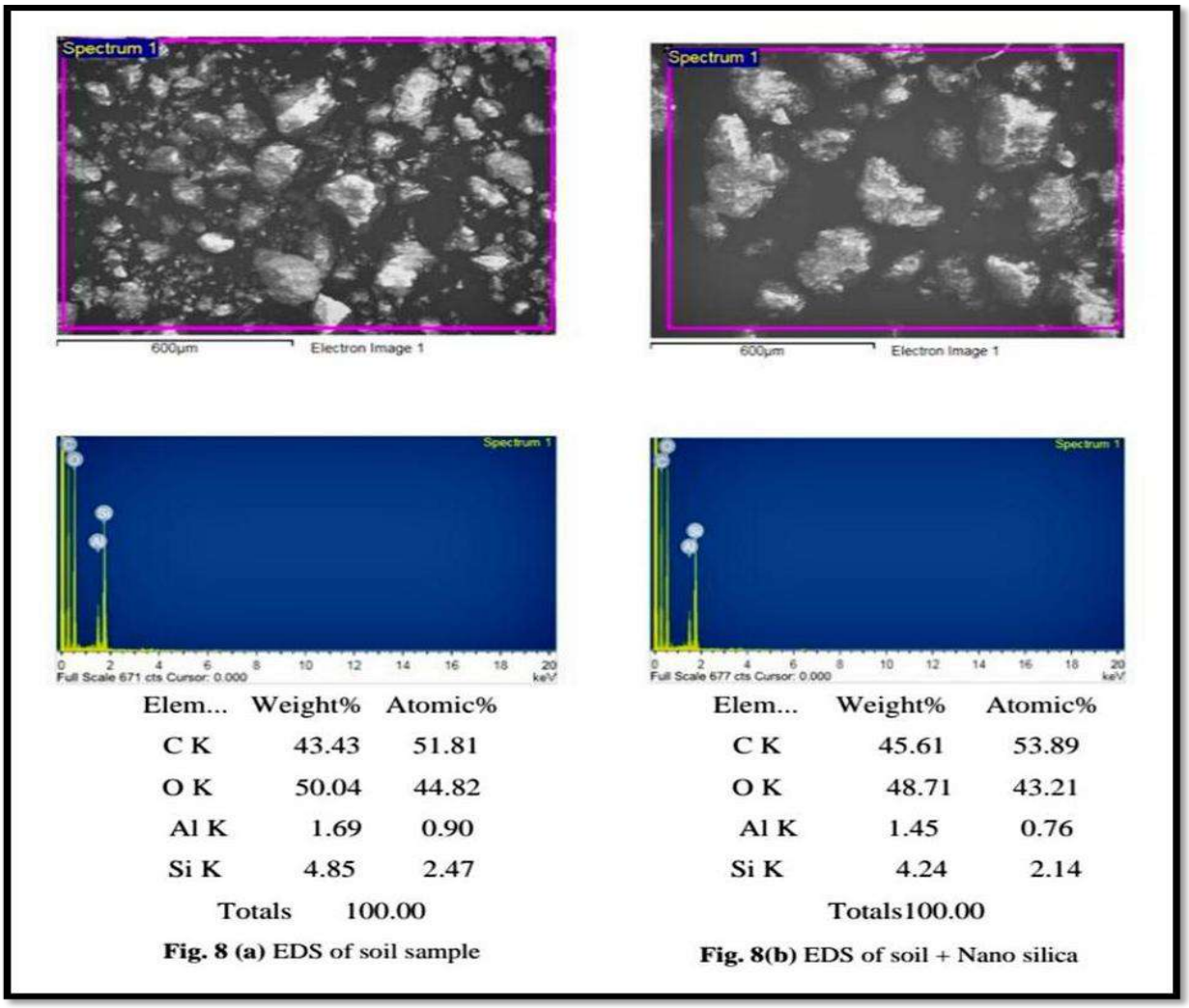


Fig. 7. SEM images of soil specimens (a) untreated soil (b) soil stabilized with Nanosilica

3.5 Energy-Dispersive X-RAY Spectroscopy (EDS) Fig 8 (a), (b) shows the EDS of soil, soil + Nano-silica, samples. From EDS analysis it is observed that the component of soil nearly equal to the components of soil with Nano-silica mixture, it means Nano-silica cannot do any chemical reaction with soil EDS test is used for analysis of elements and chemical characterization of a sample. It depends on an interaction of few sources of X-Ray excitation and sample. The Basic study of this analysis is to know each element has a unique atomic structure allowing unique set of peaks in its X-Ray emission spectrum.



Elem...	Weight%	Atomic%
C K	43.43	51.81
O K	50.04	44.82
Al K	1.69	0.90
Si K	4.85	2.47
Totals	100.00	

Fig. 8 (a) EDS of soil sample

Elem...	Weight%	Atomic%
C K	45.61	53.89
O K	48.71	43.21
Al K	1.45	0.76
Si K	4.24	2.14
Totals	100.00	

Fig. 8(b) EDS of soil + Nano silica

3.6 Compaction characteristics

The variation in the maximum dry density and the optimum moisture at different percentage of cement and additive is illustrated in Figs. 3Fig. 4, Fig. 5 and 6. There were three replicates done to ensure the reproducibility and average value of the MDD and OMC were taken into consideration. It has been noticed that the addition of 3 % cement in the soil led to an increase in the optimum moisture from 11 % to 12 %, whereas the maximum dry density decreased from 1.771 to 1.723 g/cm3. This enhancement in the OMC can be attributed to the increase in specific area, which results in requirement of large amount of water to hydrate the soil particles. Further, the decrease in MDD can be explained due to the flocculation and agglomeration and the cementation of the soil particles, which have been reported in previous works

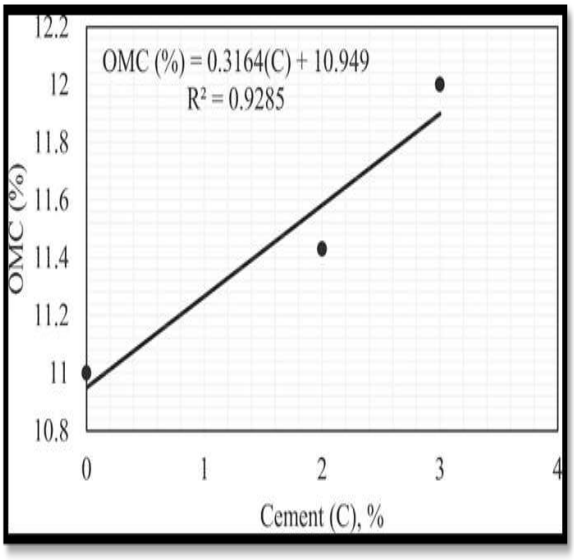


Fig. 3. Optimum moisture content vs cement content.

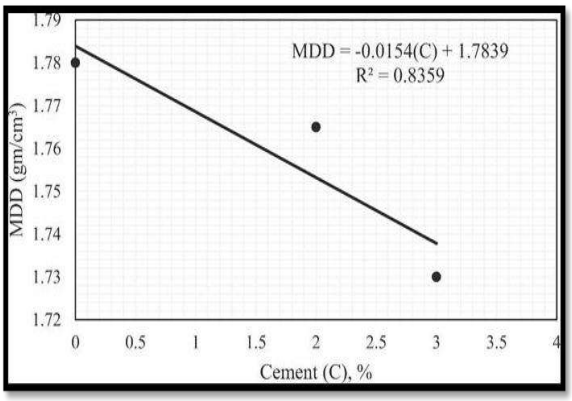


Fig. 4. Maximum dry density vs cement content.

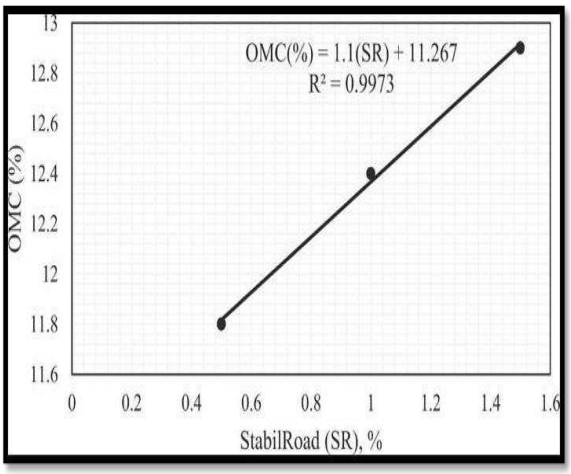


Fig. 5. Optimum moisture content vs additive content.

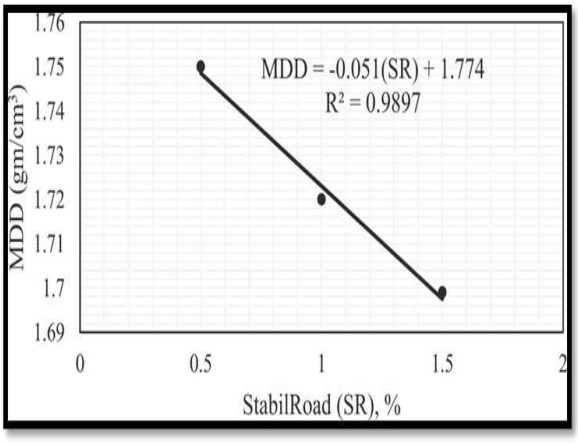


Fig. 6. Maximum dry density vs additive content.

3.7. California bearing ratio

CBR value of the sandy-clayey soil under unsoaked and soaked conditions were tested and found to be 9.0 % and 3.8 %, respectively. On introducing cement to the soil, CBR values increased by 172.22 % and 181.58 %, respectively, which indicates an increase in strength and stiffness of the mixture as shown in Fig. 7. This increase in strength can be attributed due to the attractive forces and the capillary action between the large cluster of cement, clay, and the cement gel [52]. As stated in IRC SP 89 [53], the minimum percentage of cement should be selected, that achieves the minimum specified CBR and it should also incur a lower cost of the subgrade. Therefore, 2 % of cement was chosen as the optimum amount based on these two criteria.

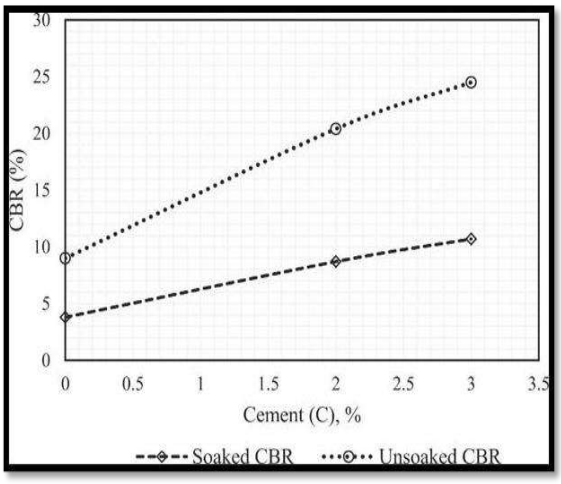


Fig. 7. CBR test results.

3.8. Unconfined compressive strength (UCS)

UCS test has been carried out to assess the effectiveness and contribution of the additive for modifying the strength of soil mixture. The increase in the percentage of the additive on the cement modified soil significantly improved compressive strength of the specimens, as shown in Fig. 9. The compressive strength of soil mixture increased by 70.15 % for 7 days curing period and 88.36 % for 28 days curing period with an increase in the additive content from 0 % to 1.5 %. A significant jump of 23.68 % for 7 days and 42.84 % for 28 days were found as the additive content increased from 0.5 % to 1.0 %, although there was a marginal increase beyond 1 %. This same trend has been exhibited as shown in the CBR test results. Further, the effect of curing time on the specimens containing different percentages of the additive was also observed. It was found that the mixtures attained sufficient strength within the first 7 days of curing. For

example, the 1 % additive content treated had a compressive strength of 745.2 kPa, which is 54.77 % more than the compressive strength of the soil-cement mixture. Hence, 1 % additive was chosen as the optimum content to be used in the cement modified soil mixture.

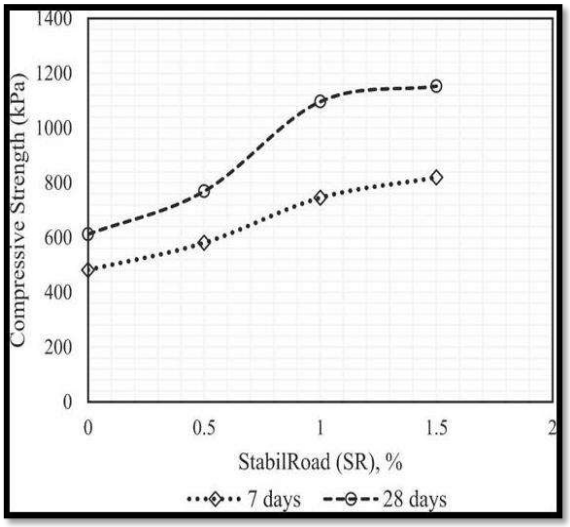


Fig. 9. Unconfined compressive strength test results.

3.9. Economic analysis

The flexible pavement for the rural road sections was designed based upon the soaked CBR values as mentioned in the chart shown in IRC SP 72-2015 [66]. The soaked CBR values taken for study were 3.8 % for soil mixture, 8.7 % for cement modified soil mixture and 15.0 % for Stabil Road cement modified soil mixture. The overall thickness required at different traffic loads varying from 10 to 2000 Equivalent Single Axle Load (measured in thousands) was calculated for each soaked CBR as shown in Fig. 14. It can be clearly seen from the figure that inclusion of cement to the soil mixture resulted in reduction of thickness varying from 26 % to 46 % in comparison with the untreated soil mixture. Furthermore, inclusion of this additive to the cement modified mixture resulted in further reduction varying from 30.43 % to 55.35 % as compared to the soil mixture. As thickness required by the additive mixture is less compared to the other treatments applied, there would be less requirement of materials and less utilization of transportation which ultimately leads in minimizing the carbon footprints.

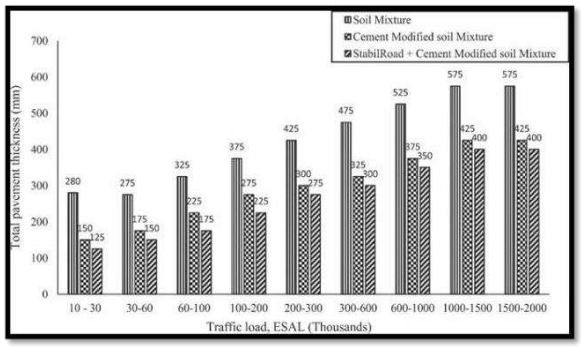


Fig. 14. Total required pavement thickness (mm) at different traffic loads (ESAL).

In order to check the viability of the additive in the cement modified mixture, the cost of the overall pavement was compared. Three types of pavement A–C (as shown in Fig. 15), which were designed using CBR values for untreated soil mixture, 2 % cement modified soil mixture and 2 % cement modified soil mixture containing 1 % additive, were taken into consideration for this study. For the present analysis, traffic load was assumed to be 1000–1500 ESAL and a 7 m width of the pavement carriageway was taken with the length of the section assumed to be 1 km. For determining the cost of pavement, the volume of the material required at each thickness was computed and then it was multiplied by the rates given by CPWD [67] and the price of the additive and its construction cost was taken from its one of the distributors in India [68]. The amount of material required for each thickness, machinery, transportation and labor cost were only taken into consideration for computing the cost of the pavement. As seen from Fig. 16, the pavement with composition C which had StabilRoad in the cement modified soil mixture resulted in saving 42.48 lakhs rupees which is approximately $55,914 per km as compared to the Pavement A which had untreated soil mixture. Further, the Pavement C also had Rs. 6.55 lakhs rupees lower cost which is approximately $8619 cost per km as compared to the Pavement B which had cement modified mixture. The cost comparison indicates that this additive not only results in improving the engineering properties of the soil and reducing the carbon footprints but it also saves the cost of the overall pavement.

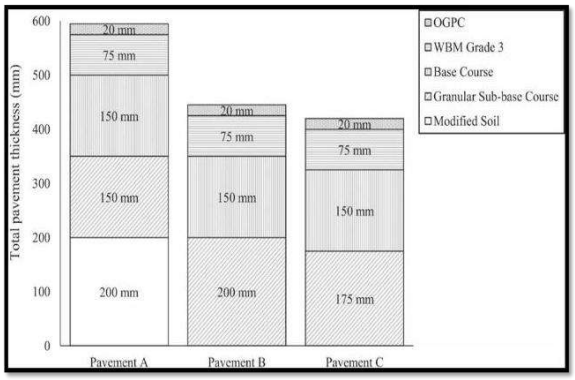


Fig. 16. Overall cost of pavement with and without modified soil mixture.

IV. CONCLUSIONS

Nowadays, Analysis on the application of Nanomaterials has become a large topic follow from economic advantage. To review the result of nano-material on engineering properties of soil, an experimental program was carried out by adding Nanosilica on the soft soil. The following Conclusions can be taken from the Experimental outcomes.

1. "The MDD values of soft soil initially increased with addition of" Nanosilica then decreased after optimum. "The MDD value" increases up to 1% of Nanosilica thereafter its value consistently decreased. In the other hand OMC has continuously decreased" with by using nanosilica in soil.
2. The UCS values of soft soil without curing increases up to 1.5% of Nanosilica and after that decreases.
3. Both the CBR soaked and unsoaked values increases with use of up to 1% nanosilica. Soaked CBR value gives better result for both subgrade and pavement construction."
4. Inclusion of nanosilica to the soil it showed formation of a very dense matrix SEM image in which pores were filled to a large extent and interlock between the particles increases which helps to improve the strength of soft soil.

In this paper, it is noticed that the method of soil stabilized with Nanosilica and is a considerably applied method of ground improvement, which increases the shear strength, UCS, and both soaked and unsoaked CBR of soil. Because of this, it increases the stability of structures, i.e. foundation and roadbed. This improvement technique can be considered as a practical method for improvement of mechanical behaviours of soil in civil engineering project.

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Design of Flexible Pavement

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Abstract- Flexible pavement is a primary component of modern transportation infrastructure, designed to distribute traffic loads through layered construction to ensure durability and serviceability. This study presents a comprehensive approach to the design of flexible pavement, focusing on the site-specific requirements near Safedabad. The core methodology involves systematic traffic volume analysis, subgrade soil investigation, and the determination of California Bearing Ratio (CBR) values in accordance with Indian Roads Congress (IRC:37-2018) guidelines. By integrating critical parameters such as design life, vehicle damage factors, and cumulative standard axles (MSA), the study calculates optimal layer thicknesses for bituminous surfacing, base, and sub-base courses. Structural analysis, facilitated by computational tools, ensures the pavement's resistance to fatigue cracking and rutting under anticipated traffic conditions. The findings demonstrate that adhering to rigorous material testing and compaction techniques significantly improves pavement lifespan and reduces long-term maintenance costs. Ultimately, this research provides a technical framework for engineering resilient road infrastructure capable of supporting modern traffic demands while maintaining safety and operational efficiency.

I.INTRODUCTION

Transportation networks serve as the backbone of economic and social development, with road infrastructure playing a crucial role in regional connectivity. Flexible pavements, characterized by their ability to transmit loads through layered action, remain the most widely adopted construction type due to their cost-effectiveness and flexibility under varying environmental conditions. A well-designed pavement must withstand dynamic traffic loads and climatic stressors over its projected design life, necessitating a scientific approach to material selection and structural composition.

The primary objective of this project is to apply engineering principles to design a robust flexible pavement structure for a site located near Safedabad. This research addresses the necessity of pavement design by evaluating key variables, including traffic composition, subgrade bearing capacity, and drainage requirements. By conducting field surveys and laboratory tests—such as bitumen penetration, ductility, and aggregate impact value—the study seeks to align empirical design methods with actual field conditions. Furthermore, this project adheres to established standards, specifically the IRC:37-2018 guidelines, to ensure that the proposed layers, from the sub-grade to the bituminous concrete, are engineered for optimal load transfer and structural integrity. This report details the methodology, testing procedures, and design calculations employed to create a reliable and sustainable road design, providing a scalable model for civil engineering applications.

II. LITERATURE REVIEW

IRC:37-2018: Guidelines for the Design of Flexible Pavements

This document serves as the primary technical code for the project. It provides the mandatory framework for the mechanistic-empirical design of bituminous-surfaced roads, applicable to national and state highways. Key elements covered include estimating cumulative traffic in Million Standard Axles (MSA), evaluating subgrade strength via CBR, and selecting pavement layers (e.g., GSB, DBM, BC). The 2018 revision emphasizes controlling specific structural distresses—fatigue cracking and rutting—by validating the design against performance-based limiting values.

IS: :73–2013: Specification. Bureau of Indian Standards.
This series of Indian Standards is referenced for the systematic laboratory evaluation of subgrade soil. It defines the standard procedures for critical soil characterization, including grain size distribution, Atterberg limits, Maximum Dry Density (MDD), Optimum Moisture Content (OMC), and the California Bearing Ratio (CBR) test. The accurate determination of these soil parameters is essential, as the subgrade strength directly dictates the required pavement thickness in the IRC design process.

IIT-PAVE Software Documentation
IIT-PAVE is utilized as a computational verification tool within the project to perform structural analysis of the pavement layers. Based on layered elastic theory, this software allows engineers
to calculate critical strain values at the bottom of the bituminous layer and the top of the subgrade. By comparing these calculated strains against the limiting criteria defined in IRC:37-2018, the software ensures that the proposed pavement design can safely withstand fatigue and rutting throughout its intended design life.

Shreddedt. wami (2012)
In this paper the Use of waste plastic in the construction of bituminous Road. They concluded that plastic waste conforming of carry bags, mugs and other employed plastic could be used as a coating over summations and this carpeted gravestone could be used for Road construction.

Debashish Kar (2013)
performed a exploration to learn about the effect of application of coconut fiber is used as modifiers or stabilizer in and added substance in BC was formerly decided via Marshall stability test is used for the good result. For assessing strength and characteristics of bituminous paving blend Marshall Mix design fashion is a standard exploration system, which is habituated world wide. From different test it's concluded that SMA with the operation of coconut fiber force veritably proper result and it is good and can be used in flexible pavement

Suresh.T et.al (2013)
conducted a exploration to find out about the effect of application of natural fiber as coconut fiber is employed as stabilizer in SMA & cumulative in BC used to be decided by means of Marshall check & verified accurate result. Marshall Mix graph is a trendy laboratory system, which is espoused transnational for relating & reporting the electricity & go with the inflow traits of bituminous paving composites. From exclusive take a look at it's concluded that SMA with the operation of sisal fiber provides veritably suitable end result & can be used in flexible pavement.

A.A Md. Maniruzzaman et.al (2015)
conducted research to recognize to look at the impact of cellulose oil palm fibers content material on the rheological homes of 80-100 penetration grade bitumen. Preliminary take a look at are carried out the comfortable the requirement of the study. Viscosity, softening factor and penetration check had been used to represent the asphalt binder. The conclusion derived from the learn about that the amendment of 80-100 binder with 0.4% COPF offers the choicest enchantment of rheological properties.

Sandip Karmakar and Tapas Kumar Roy (2016)
conducted a exploration to fete the application of waste plastic & waste tire rubber with bitumen for structure of roads in low – budget60/70 grade bitumen had been used as the base bitumen for polymer correction distinct commotional take a look at are carried out and the consequences that tattered recycled waste plastics is fiscal alternately than eating raw polymer for acclimate the bitumen. The goods point out that addition of 1 through weight of combined plastic and bedeck the trait of pavement.

Kalta Bhanuprasad et.al (2018)
carried out a lookup to fete the conduct of damage heat combine asphalt AS regulation power duos and can be used for all climates and caller conditions. The abecedarian take a look at of bitumen are performed and Marshall Fusions plan and humidity vulnerability check used to be carried out in agreement their performance. It's concluded that the modified bitumen combinations would be a choice answer for the protection of city roads and with lower pollution.

Ashpaq Majeed Naik, Dr. Rakesh Gupta (2018)
The study had two major and critical goals which

covered by considering the following three tasks, the first was the visual evaluation and inspection of existing flexible pavement conditions including the failures, the second to determine and find out the actual causes of these failures in the pavement, and the third is to select the most and effective treatments and maintenance types. As a case study, of Ambala Cantt to Saha road was selected for evaluation and inspection purposes. The field evaluation works were achieved on the existing flexible pavement conditions of the selected rural highway. The results were most of the damages and failures in the pavement are serious and extreme surface deformation, cracks, disintegration, and surface defects. These damages and failures are caused by fatigue and other types of failures resulted from the movement of heavy vehicles and trucks, poor drainage design, unsuitable pavement layers thickness design, and improper pavement mix design and selected materials.

Amit Kundal and Dr. Amit Goel (2019)
introduced a fashion to decide the advantages of use of naturally on hand fiber known as sisal fiber used as cumulative in Bitumen concrete organized after fixing the owner of admixture & colorful. Research skilled that sisal fiber performs advanced that different fiber. Marshall balance nice is considerably & in numerous cases used for pavement workshop. Through Marshall places stability, drift value, air used. In the check it's discovered that the use of fiber us a cumulative embellish the houses like places like, stability, energy and drop the drain down of bitumen concrete BC.

Rohit Raj, Ritesh Kumar Yadav, Km Esha Jaishwal, Dr. Shiv Kumar (2024)
The extensive use of plastic wrappers for items like betel nuts, chocolates, chips, handbags, and cold drink bottles presents significant environmental and economic challenges. The production and disposal of these wrappers consume substantial energy and resources, contributing to environmental harm. While industries Favor plastic for its lightweight, inexpensive, and sturdy qualities, a potential shift to alternative materials like paper and wood may worsen environmental issues. Polyethylene, Polystyrene, and Polypropylene, the main components of plastic, resist easy decomposition in the environment. This study emphasizes the importance of utilizing plastic in construction processes, particularly through the heating and coating of plastics on aggregates at 160˚C, minimizing air gaps and enhancing stability. Proper disposal of non-biodegradable plastic remains challenging due to insufficient landfills. Research suggests that incorporating waste plastics into road construction materials results in stronger, more damage-resistant, and cost-effective roads. In India, roads adhere to specific guidelines with bituminous concrete layers over a granular base, utilizing Bitumen Grade VG-30 and specific aggregate sizes. The addition of polymers to road materials offers advantages such as increased longevity, damage resistance, cost-effectiveness, reduced maintenance, effective insulation, and diminished noise pollution, contributing to a more sustainable construction approach.

III. METHODOLOGY

Methodology refers to the systematic procedure adopted to achieve the objectives of the project. In this project on Design of Flexible Pavement, the methodology explains the step-by-step process followed for data collection, analysis, design calculations, and final pavement thickness determination based on standard guidelines. The methodology has been developed in accordance with the recommendations of IRC:37-2018 and standard pavement engineering principles, ensuring accuracy, reliability, and practical applicability.

Traffic Data Collection The collected data was used to calculate the cumulative number of standard axles during the design life of the pavement.

Soil Sampling and Subgrade Investigation These properties helped in evaluating the strength and bearing capacity of the subgrade.

Determination of CBR Value the California Bearing Ratio (CBR) test was conducted as per IS:2720 guidelines. The test measures the resistance of subgrade soil to penetration, which directly influences pavement thickness.

Determination of Design Traffic This calculation forms the backbone of the pavement design process.

Selection of Design Life The design life for the flexible pavement was selected based on IRC recommendations and functional classification of the road.

Urban roads: 15 years
National highways: 20 years Rural roads: 10 – 15 years

Pavement Design Procedure Based on IRC:37-2018, the pavement design.

Structural Analysis Structural analysis was performed to ensure that the pavement can withstand imposed traffic loads and environmental conditions. Critical strains were checked at:

- Bottom of bituminous layer (fatigue cracking)
- Top of subgrade (rutting)
- Software tools such as IITPAVE were used for verification.

Result
Traffic near Safedabad shows clear peak-hour congestion trends Evening period is most critical Suggest:

- Signal control or roundabout improvement
- Lane widening
- Traffic police deployment during peak hours

PARAMETERS	OBSERVATION
Dominant Mode	2-Wheelers (~48%)
Peak Period	Evening (5 PM – 7 PM)
Heavy Vehicles	More during night hours
Congestion	High during evening peak
Traffic Nature	Mixed (local + through traffic)

The literature survey clearly indicates that flexible pavement design has evolved through various stages of innovation, supported by continuous research by renowned scientists and institutions. These contributions have transformed pavement engineering into a scientifically structured discipline that combines theory, experimentation, and practical field observations. This chapter forms the academic and technical basis for subsequent design procedures discussed in the following chapters.

IV. CONCLUSION

Survey work and testing form the foundation of scientific pavement design. Without accurate data regarding traffic, soil properties, and material characteristics, the pavement structure cannot be designed effectively. Proper implementation of surveys and tests ensures that the flexible pavement will perform satisfactorily under heavy traffic loads and varying environmental conditions throughout its design life. Therefore, comprehensive survey work and systematic testing are essential for achieving a durable, economical, and sustainable flexible pavement structure.

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PERFORMANCE EVALUATION OF PHASE CHANGE MECHANISM (PCM) BALL – INTEGRATED CONCRETE: STRENGTH AND THERMALREGULATION

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Abstract - *The construction industry consumes a large amount of energy, especially for heating and cooling buildings, which contributes to greenhouse gas emissions. To improve energy efficiency, this study explores the use of Phase Change Materials (PCMs) in concrete. PCMs can absorb heat when temperatures rise and release it when temperatures drop, helping to maintain stable indoor conditions. In this research, paraffin wax is used as the PCM and is enclosed inside small spherical balls to prevent leakage, then embedded into concrete cubes. Each cube contains two PCM balls and is tested for compressive strength, ultrasonic pulse velocity (UPV), and thermal performance, with results compared to normal concrete. The findings show that adding PCM balls slightly reduces the concrete's strength due to weaker bonding and small voids, but the strength still remains within acceptable limits. At the same time, the thermal performance improves significantly, as the PCM helps delay temperature rise and retain heat for longer periods. This means buildings made with such concrete could require less energy for heating and cooling. Overall, although there is a small reduction in strength, the improved thermal efficiency and durability make PCM-integrated concrete a promising and sustainable construction material.*

***Key Words*: Phase Change Materials (PCM), PCM concrete, paraffin wax, thermal energy storage, sustainable construction, energy efficiency, compressive strength, ultrasonic pulse velocity (UPV), thermal regulation, encapsulation technique**

1. INTRODUCTION

This section introduces the study. Modern construction requires both structural safety and energy efficiency, as a large portion of building energy is used for heating and cooling. Therefore, materials that can regulate indoor temperature are increasingly important. Phase Change Materials (PCMs) are effective for thermal energy storage because they absorb and release heat within a narrow temperature range, helping maintain stable conditions.

Concrete is widely used due to its strength and durability, but it has poor thermal performance, leading to higher energy consumption. To improve this, PCMs such as paraffin wax can be incorporated into concrete. However, direct mixing may cause leakage, reduced strength, and durability issues. To address these challenges, this study uses a macro-encapsulation method, where PCM is enclosed in spherical balls and embedded into concrete. This approach reduces leakage and limits the impact on mechanical properties. The study aims to evaluate compressive strength and thermal performance of PCM-integrated concrete, highlighting its potential for energy-efficient and sustainable construction.

1. LITERATURE REVIEW

Research on Phase Change Materials (PCM) in concrete shows a clear balance between improved thermal performance and reduced mechanical strength. Studies consistently report that PCM enhances thermal energy storage by absorbing and releasing heat, helping regulate temperature in buildings. However, this benefit often comes with drawbacks such as reduced compressive strength, increased porosity, and potential durability concerns due to weak bonding between PCM and the cement matrix.

A 2022 review highlighted that PCM improves thermal storage regardless of the incorporation method, but strength loss remains a key challenge. Macro-encapsulation, especially non-contact methods, is considered more effective as it minimizes direct interaction between PCM and concrete, preserving structural integrity. One notable approach is the use of hollow steel balls filled with PCM, which offer better containment and thermal conductivity. Dong et al. demonstrated that such systems provide high latent heat

capacity (around 200.5 J/g) with minimal leakage even after repeated thermal cycles. Their results also showed that PCM-integrated concrete can reduce indoor peak temperatures by 25–33% and delay heat transfer.

Despite these advantages, increasing PCM content leads to a reduction in compressive strength. For example, strength decreased progressively with higher PCM replacement levels, mainly due to weak bonding between smooth PCM surfaces and the cement matrix. However, even the lowest strength values remained within acceptable structural limits, indicating practical usability.

Several other studies support these findings. Adesina (2020) and Sharma et al. (2022) emphasized improved thermal efficiency and reduced energy demand but noted strength and durability concerns. Zhang et al. (2013) and Wei et al. (2017) highlighted the importance of proper encapsulation to prevent leakage and improve durability. Sakulich et al. (2012) and Memon et al. (2015) reported better thermal regulation but reduced strength due to lower density and weak bonding. Pilehvar et al. (2017) found microencapsulation effective but costly, while Feno Llera et al. (2013) observed reduced workability in fresh concrete. More recent work by Wang et al. (2026) suggests that adding fibres can help recover some strength, though it increases system complexity.

Overall, these studies confirm that PCM-integrated concrete offers significant thermal benefits and energy savings, but careful design is required to balance thermal performance with structural strength.

2. METHODOLOGY

The study follows an experimental approach including material selection, PCM encapsulation, concrete casting, curing, and testing. Paraffin octadecane is used as the Phase Change Material (PCM) because it is suitable for building temperature regulation. The PCM is filled into hollow steel balls using a vacuum process and then sealed with epoxy to prevent leakage. These PCM-filled balls are used as partial replacement of coarse aggregate in concrete.

Concrete mixes are prepared with different replacement levels of PCM balls (0%, 25%, 50%, 75%, and 100%) using M25 grade concrete. A constant water–cement ratio is maintained, and a superplasticizer is added to improve workability. The PCM balls are added at the final stage of mixing to avoid damage. Concrete cubes of size 150 mm × 150 mm × 150 mm are cast, each containing two PCM balls placed evenly.

The specimens are cured in water for 7, 14, and 28 days. Tests conducted include compressive strength, ultrasonic pulse velocity (UPV), and thermal performance using infrared temperature measurements. These tests are used to evaluate both the strength and thermal behavior of PCM-integrated concrete for possible use in energy-efficient buildings.

3. System Architecture of Ball-Integrated Concrete

The system of ball-integrated phase change concrete works in four main steps: PCM selection, concrete preparation, thermal regulation, and strength checking.

First, a suitable Phase Change Material (PCM) is selected and filled into hollow steel balls. These balls prevent leakage and help transfer heat efficiently.

Second, the PCM-filled balls are added into concrete by partially replacing coarse aggregate. During high temperature, the PCM absorbs heat and melts, reducing temperature rise. When temperature drops, it solidifies and releases heat, helping maintain stable temperature.

Third, the system improves thermal performance by reducing temperature peaks and fluctuations, which helps in energy savings for buildings.

Finally, the strength of concrete is tested. Since steel balls reduce bonding with cement, compressive strength decreases as more PCM balls are added. Therefore, a proper balance is needed between strength and thermal benefits.

Overall, this system improves thermal comfort and energy efficiency while maintaining usable structural strength.

4. Results and Evaluation

The results of this study show that ball-integrated Phase Change Material (PCM) concrete significantly improves thermal performance. The inclusion of PCM-filled steel balls helps in reducing indoor temperature and delaying the peak heat time compared to conventional concrete. In experimental studies, the peak indoor temperature was observed to drop considerably when PCM panels were used, confirming that the latent heat storage capacity of PCM effectively absorbs excess

heat during high-temperature conditions and releases it slowly when the temperature decreases. This process helps in maintaining a more stable and comfortable indoor environment.

The thermal performance improves as the amount of PCM balls in the concrete increases. This is because a higher PCM content allows more heat energy to be stored and released during phase change, which reduces sudden temperature fluctuations. As a result, PCM-integrated concrete can reduce the dependence on artificial cooling systems and improve overall energy efficiency in buildings.

However, the mechanical performance shows a declining trend with increasing PCM content. The compressive strength of concrete decreases as more PCM balls replace the natural coarse aggregate. This reduction in strength is mainly due to the weak bonding between the smooth steel surface of the PCM balls and the cement matrix, which creates interfacial gaps and reduces load-bearing capacity. Despite this reduction, lower and moderate replacement levels still maintain acceptable structural strength.

Overall, the results clearly indicate a trade-off between thermal efficiency and mechanical strength. While higher PCM content improves temperature regulation, it negatively affects strength. Therefore, an optimized replacement level is necessary to achieve a balance between both properties. Moderate use of PCM balls provides the best performance by offering significant thermal benefits while maintaining sufficient structural integrity.

CONCLUSIONS

This study concludes that ball-integrated Phase Change Material (PCM) concrete is an effective solution for improving thermal performance in buildings while maintaining acceptable structural strength. The use of PCM-filled steel balls helps control indoor temperature by absorbing heat during high temperatures and releasing it during cooling periods, which reduces peak temperatures and improves thermal comfort.

Results show that thermal efficiency increases with higher PCM content. However, compressive strength decreases due to weak bonding between the steel balls and the cement matrix. Despite this reduction, the concrete still performs adequately for non-structural and semi-structural applications. A balanced replacement level of about 25–50% coarse aggregate with PCM balls is found to be optimal, providing a good compromise between strength and thermal benefits. Overall, this material shows strong potential for sustainable construction, especially in building elements like walls and panels where thermal regulation is important. It helps reduce energy consumption and supports energy-efficient building design.

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