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A Statistical Comparison of the Mechanical Properties of Lime Pozzolana Concrete Activated with Sodium Silicate Gel

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Abstract

In the construction field, Concrete is one of the most essential materials, second only to water. However, the production of cement, a key component of concrete, is a major contributor to global carbon dioxide (CO_2) emissions, leading to environmental pollution, global warming, and climate change. Cement manufacturing requires high energy consumption and releases significant CO_2 due to the chemical transformation of limestone into clinker.In this study, two specific mix design ratios of lime pozzolana concrete, following the relevant Indian Standard (IS) code, were used to develop structural-grade concrete. The concrete specimens were cured using the wet hessian method to enhance hydration and strength development. Mechanical properties, including compressive strength, split tensile strength, and flexural strength, were evaluated at 7, 28, 56, and 91 days. The test results met the strength requirements outlined in the IS code, confirming the feasibility of lime pozzolana concrete as a sustainable alternative to traditional cement-based concrete.Furthermore, statistical analysis was conducted to optimize the two mix proportions and assess the correlation between compressive strength and both split tensile and flexural strength. The results provide valuable insights into the structural performance of lime pozzolana concrete, reinforcing its potential as an environmentally friendly construction material. By offering comparable mechanical properties while reducing cement usage, lime pozzolana concrete presents a viable solution for sustainable construction practices, helping to mitigate the adverse environmental impacts of cement production.

Keywords: Hydraulic lime,fly ash, sodium silicate gel, lime pozzolana concrete, wet hessian curing, statistical analysis, sustainability.

1. Introduction

Portland cement has hugely replaced lime-pozzolan binders in modern construction due to its faster setting time and higher early strength [13], [14], [15]. The production of Portland cement involves mixing dry calcite and clay, crushing them, and heating the dry mixture in kilns at approximately 1450°C to form clinkers of cement. Gypsum is then added to the clinkers and crushed into the size of fine powder to produce the final product. However, cement manufacturing accounts for 5% to 8% of global CO_2 emissions and requires significant energy, primarily fuel. To reduce the environmental impact, industrial by-products like fly ash, silica fume, rice husk ash and ground granulated blast furnace slag (GGBS) could be combined with lime to form pozzolanic binders[10], [19]. In this reaction, silica from the pozzolan interacts with calcium from hydraulic lime which forms a gel of calcium silicate hydrate (C-S-H), could serve as a sustainable alternative to cement [13], [14], [15], [16], [17], [18].

By adopting this approach, natural clay used in cement production can be minimized, energy consumption for fuel can be reduced, and CO_2 emissions can be significantly lowered in the environment. From an environmental and sustainability perspective, lime and lime-pozzolan binders are regaining attention as a viable alternative in construction industries [19], [20].

Lime Pozzolana Concrete (LPC) is a type of building material that combines hydraulic lime, a naturally occurring binder, with pozzolana. Pozzolana mainly consists of compositions of siliceous or aluminous material that exhibits cementitious properties when blended with hydraulic lime and water. This combination results in a chemical reaction that forms a durable and stable binding material. The blend creates eco-friendly and cost-effective concrete widely used in construction projects, especially in regions where access to Portland cement is limited or where sustainable building practices are prioritized.

The hydraulic lime in LPC provides an excellent binder with self-healing properties that enhance the durability of structures. Pozzolana, on the other hand, contributes to increased strength, chemical resistance, and long-term stability [10]. The synergy of these materials not only reduces the dependency on energy-intensive Portland cement but also helps in repurposing industrial by-products like fly ash and natural volcanic ash, contributing to a circular economy[19].

This form of concrete is particularly suitable for heritage restoration projects, rural infrastructure, and low-cost housing, where traditional construction techniques and modern sustainability requirements converge [21]. Its low heat of hydration makes it ideal for mass concrete applications, reducing the risk of thermal cracking [22], [23]. Furthermore, Lime Pozzolana Concrete's ability to resist chemical attacks, such as sulfate exposure, makes it a preferred choice for structures exposed to harsh environmental conditions [24], [25]. As a result, LPC has become an integral part of modern green construction, offering a blend of durability, affordability, and ecological benefits.

2. Literature Review

Limestone, evolved from a sedimentary rock primarily composed of calcium carbonate ($CaCO_3$), is processed into calcium oxide (quick lime) through a process involving crushing and heating in lime kilns at temperatures ranging from 900–1100 °C. During this process, carbon dioxide is released from the limestone, resulting in the formation of calcium oxide [1], [2], [3], [4]. Commonly referred to as fat lime, quick lime, air lime or aerial lime, this material hardens only through the carbonation effect with air and requires a longer setting time.

Typically, lime putty is prepared by quick lime mixed with water and allowing it to mature for at least 24 hours. This putty is widely used in building applications such as plastering, surface coatings, and architectural finishes [11], [12]. If limestone contains more than 5% magnesium oxide, it is classified as dolomite or magnesium lime [13], [14]. The chemical composition of pozzolanic additives does not significantly impact the strength or reactivity of the resulting paste [5].

Lime is abundant globally, reducing the need for extensive commercial trade compared to cement. The Asia-Pacific region accounts for significant lime availability, with China being the largest consumer of lime and lime-based products like cement. In India, states such as Andhra Pradesh, Karnataka, Madhya Pradesh, Gujarat, and Rajasthan contribute approximately 75% of the total lime production in the nation.

Lime–pozzolan binders have been used in construction since before 7000 B.C., notably in ancient masonry and iconic structures viz., Egyptian pyramids and the Great Wall of China [1], [2], [3]. In ancient times, lime combined with siliceous clay, volcanic ash, and organic additives like jaggery, blood and kadukkai to develop workable, strong and durable mortar or concrete [4], [5], [6], [7], [8], [9].

Research on ancient lime mortars suggests the need to study bio-additives thoroughly to determine whether they can replace hazardous inorganic additives in modern building materials [15]. However, with the widespread adoption of cement in civil construction, knowledge of traditional binders and their preparation methods has diminished over time. Today, lime binders are primarily used for preserving historical buildings, monuments, and temples [16], [17], [18].

3. Rationale of the study

The primary drawback of using lime and fly ash in concrete is their slow reaction process, which delays early strength gain and results in slower strength development when time increases. To overcome this, a preliminary experimental study on hydraulic lime mortars was conducted, demonstrating the feasibility of producing high-strength lime mortars. By incorporating sodium silicate gel with hydraulic lime and fly ash, it is possible to attain a 28-day compression strength contrasted to ordinary Portland cement concrete (PCC). Mechanical studies of lime pozzolana concrete (LPC) formed the basis of this research, aiming to identify optimal hydraulic lime–pozzolan and sodium silicate gel blends capable of producing structural-grade concrete.

4. Materials and Methods

4.1 Materials

Lime used in construction must contain at least 60% calcium oxide. High-purity hydraulic lime, with a purity ranging from 75% to 95%, is commonly employed in construction applications, as per IS 712:1984 and IS 6932:1973. When calcium oxide in lime reacts with atmospheric carbon dioxide, it forms a calcium carbonate precipitate, effectively sealing surface microcracks in the structure. The hydraulic lime utilized in this study was sourced from Sri Sai Venkata Teja Chemicals, Piduguralla, with a purity of 92% and a specific gravity of 2.2. Flyash was collected from VTPS-Ibrahimpatnam, having specific gravity of 2.89. Sodium silicate gel was procured from Lakshmi Chemicals, Vijayawada. Sodium silicate in concrete promotes the reaction between hydraulic lime and fly ash, improving concrete hardening and activating the chemical reaction process. Locally sourced river sand, meeting Zone II specifications, is used as fine aggregate. Its properties, determined in accordance with relevant IS codes, are as follows: specific gravity: 2.68, fineness modulus of 3.3 and moisture content of 7.8%. The coarse aggregate used was locally sourced crushed stone, comprising 60% of 20 mm size aggregate and 40% of 10 mm size aggregate [7]. Its properties, as per IS code standards, include a specific gravity: 2.78, fineness modulus of 7 and moisture content of 2%. Water plays a major role in concrete during the hydration process and increases strength of concrete construction, as its quality significantly affects strength of the concrete. The specifications for construction water usage adhere to the relevant IS 456:2000 code requirements.

4.2 Methodology

Two mix proportions, 1:2:4 (LP40) and 1:1:2 (LP20), were selected based on IS 5817:1992 recommendations. After conducting extensive trial mixes for these ratios, appropriate percentage variations of materials were determined to develop structural-grade concrete. In the present experimental study, hydraulic lime content varied in increments of 5% up to 35%, sodium silicate in increments of 7.5% up to 42.5%, with the remaining portion comprising fly ash.

All concrete mixes were prepared with a compaction factor of 0.85±0.01. Workability was assessed through compaction factor tests and slump cone tests, as specified in the IS code. Specimens were casted in steel molds, including cube, cylindrical, and beam specimens of sizes 150x150x150 (mm^3), 150 mm diameter x 300 mm length and 500x100x100 (mm^3) respectively. Three specimens are casted per each set, following IS 516:2021 guidelines. After demolding, the specimens underwent wet hessian curing for approximately 91 days. Wet hessian curing is widely used for lime-pozzolana concrete as per IS 5817:1992 as it ensures consistent moisture supply, crucial for proper hydration and carbonation. This curing method offers several benefits, including preventing cracking, improving strength and durability, enhancing workability, being cost-effective and environmentally friendly, and making it suitable for historical restoration.

Mix notations

LP40 was prepared with 40% hydraulic lime and 60% fly ash, while LP20 contained 20% hydraulic lime and 80% fly ash. The SLP40 and SLP20 mixes followed a similar pattern, where sodium silicate content varied in 7.5% increments up to 42.5% and hydraulic lime in 5% increments up to 35%, with the remainder being fly ash. These mix variations were denoted as (SLP40M1-SLP40M7) and (SLP20M1-SLP20M7).

5 Results and Discussions

5.1 Tension strength

A compression strength test was performed as per IS 516:2021. Experimental results indicate that the optimal strength was achieved at SLP40M5 and SLP20M5. The seven mix samples of SLP40 and SLP20 exhibited greater compression strength contrasted to the conventional LP40 and LP20 mixes. This improvement is attributed to the addition of sodium silicate gel, which acts as a chemical activator, enhancing the reaction between the silica content in fly ash.Throughout the hydration process, silica and aluminates from fly ash interact with calcium from hydraulic lime, forming C-S-H(Calcium Silicate Hydrate) gel and C-A-S-H(Calcium Aluminate Silicate Hydrate) gel [1]. These compounds aid in concrete hardening, enhance strength development, and promote the formation of a dense, low-porosity structure [20], [31].Additionally, the SLP20 mix demonstrated superior performance compared to SLP40 due to its higher cementitious material content. When lime content was increased to 28–35% and sodium silicate gel to 20–25%, compression strength showed an increase, as illustrated in Figures 1 and 2.The 91-day compression strength values for SLP40 mix exhibited variations of +15.11%, +01.10%, +15.66%, +14.65%, +18.01%, -11.40%, and -18.16%, whereas SLP20 mix recorded variations of +39.23%, +23.08%, +23.28%, +12.76%, +15.14%, -20.36%, and -6.15%. Additionally, the compression strength variation of SLP40 was observed to be 1.15, 1.16, 1.35, 1.54, 1.82, 1.61, and 1.32 times that of LP40, while for SLP20, the values were 1.39, 1.71, 2.11, 2.38, 2.74, 2.18, and 2.05 times that of LP20.

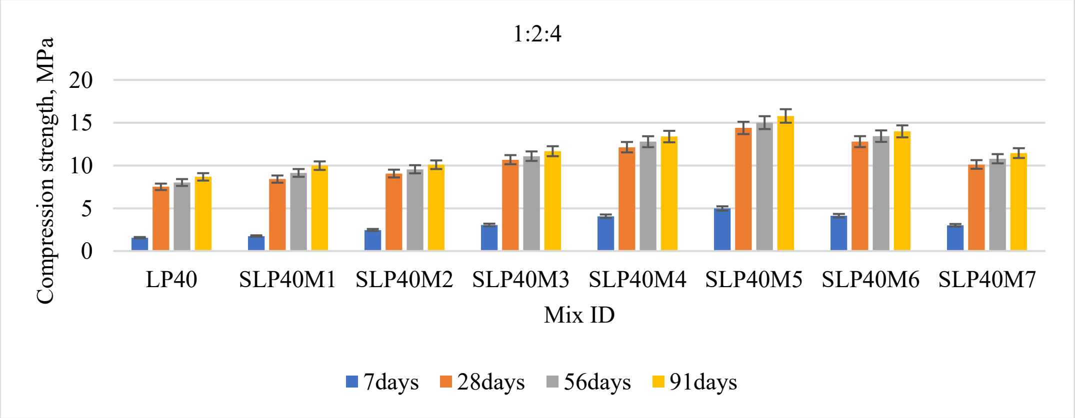

Fig 1. Graphical representation of compression strength variation with SLP40 mix

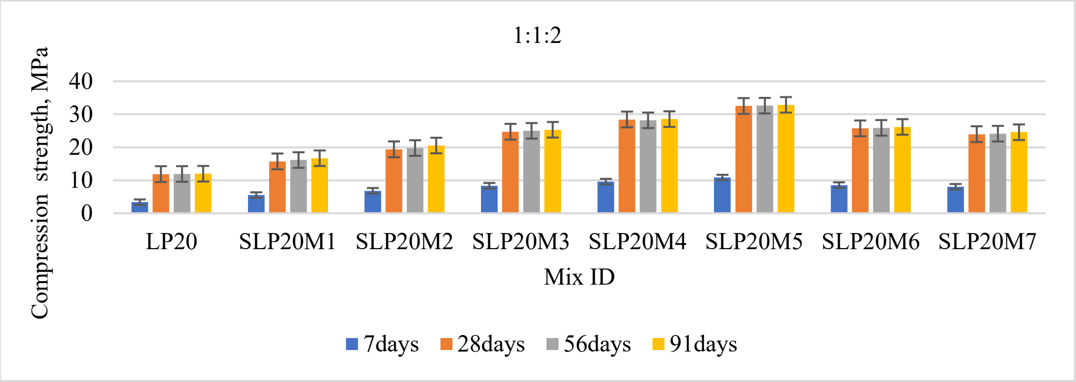

Fig 2. Graphical representation of compression strength variation with SLP20 mix

5.2 Split tensile strength

The tension strength test was conducted following IS 516:2021. The results followed a similar trend as the compression strength test, as shown in Fig. 3 and 4 for both mixes. The SLP20 mix specimens at the age of 7 and 28 days demonstrated greater improvement in tensile strength compared to the SLP40 mix specimens.

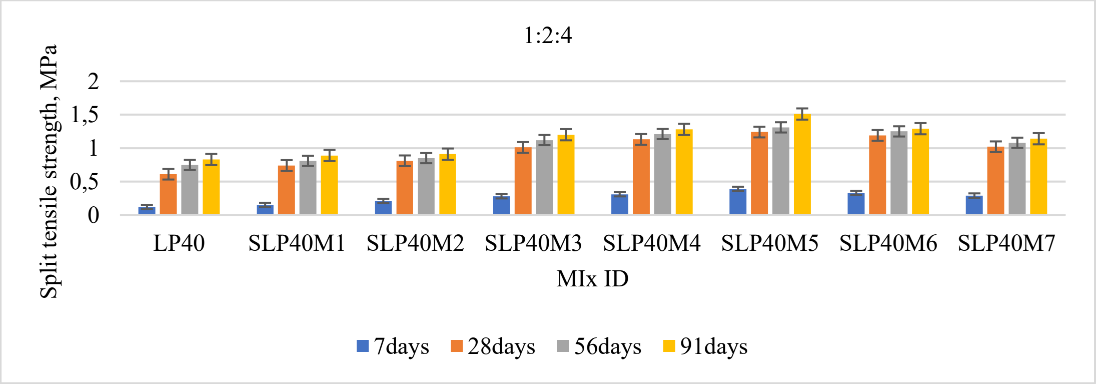

Fig 3. Graphical representation of split tensile strength variation with SLP40 mix

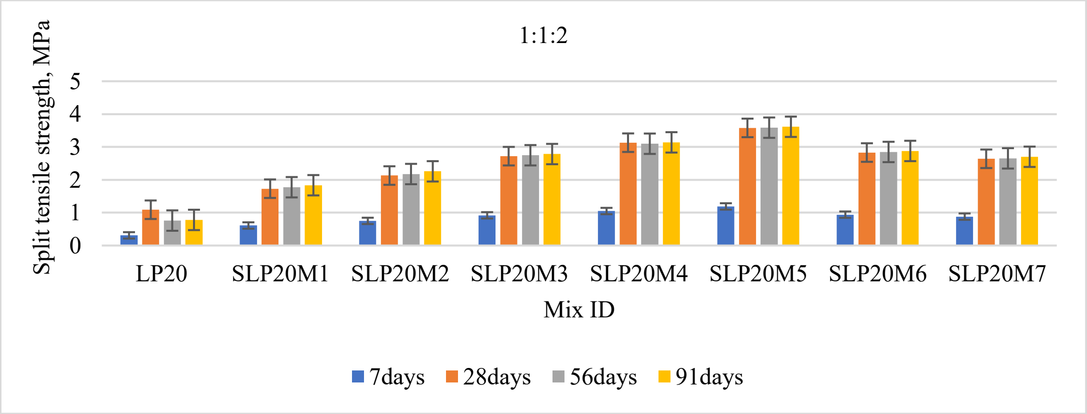

Fig 4. Graphical representation of split tensile strength variation with SLP20 mix

5.3 Flexural strength

The flexure strength test was also performed as per IS 516:2021. A comparable pattern was observed in flexure strength values, aligning with the compression strength results. The incorporation of hydraulic lime enhanced the flexural behavior of the concrete [19]. The test results for SLP40 and SLP20 mixes are presented in Fig. 5 and 6, respectively.

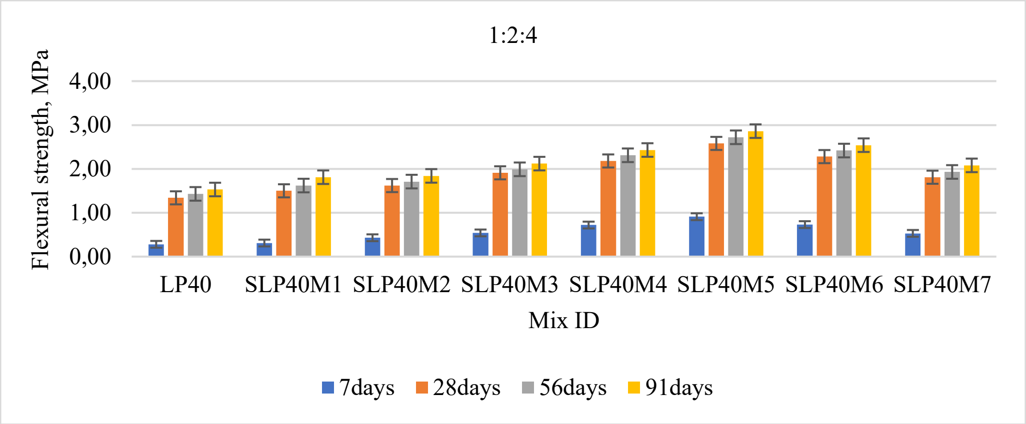

Fig 5. Graphical representation of flexural strength variation with SLP40 mix

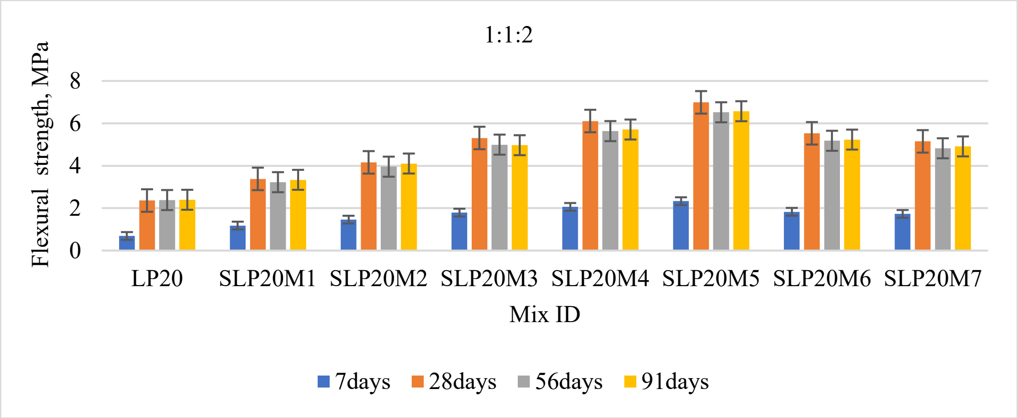

Fig 6. Graphical representation of flexural strength variation with SLP20 mix

5.4 Statistical analysis

The addition of pozzolanic materials improves the tensile strength of concrete. An extensive study conducted at the Central Road Research Institute (CRRI) laboratory established the following statistical correlation between flexural strength and compressive strength [32] for natural gravel with a maximum size of 20mm:

$y = 14.1x - 10.4$ ------ (1)

Where y is the compression strength of concrete, MPa and

x is the flexure strength of concrete, Mpa

After applying statistical analysis to all the data, the Central Road Research Institute (CRRI) established the following general relationship between the flexural and compressive strength of concrete:

$y = 11x - 3.4$ ------ (2)

Several empirical relationships exist between the tensile strength and compressive strength of concrete. One of the most commonly used relationships is:

Tensile strength = K (Compressive strength)^n------ (3)

Simply taken as $z = K(y)^n$------(4)

Where, 'K' varies from 6.2 for gravels to 10.4 for crushed rock (average value of 8.3) and 'n' vary from ½ to ¾.

The Indian Standard IS-456 of 2000 gives the relationship between the compressive strength and flexure strength:Flexure strength = $0.7\sqrt{f_{ck}}$------ (5)

Where 'f_{ck}' is the characteristic compressive strength of concrete, MPa.

Relationship between optimal split tensile strength and optimal compression strength

By statistical analysis, Fig. 7 and 8show the relationship between split tensile strength and flexure strength of optimal concrete mixes of SLP40M5 and SLP20M5. The correlation coefficients are obtained as $R^2=0.8644$ and $R^2=0.9455$. The relation between these two strengths is expressed as $y = 7.5391x^{0.9362}$ and $y = 12.973x^{0.6525}$,which satisfies the above-mentioned eq. 3 and 4. Out of these, optimal mixes of 1:2:4 and 1:1:2, the SLP20M5 mix of 1:1:2 shows good regression and maintained a good relationship.

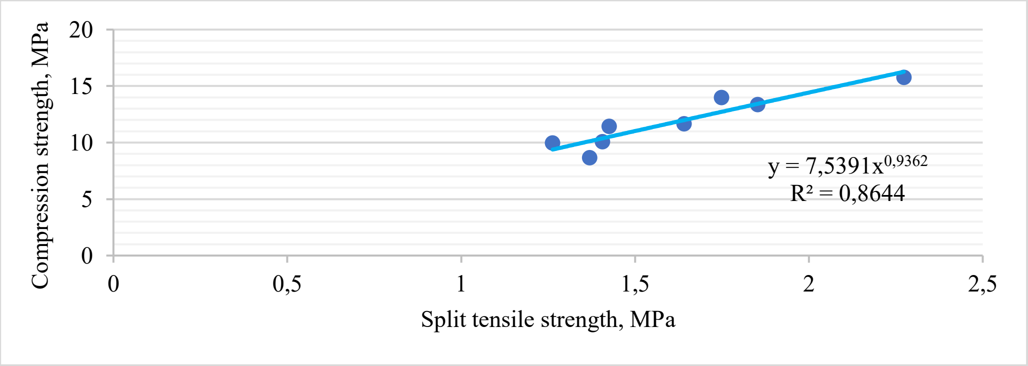

Fig 7. Relationship between split tensile strength and compressionstrength of SLP40M5 optimal mix

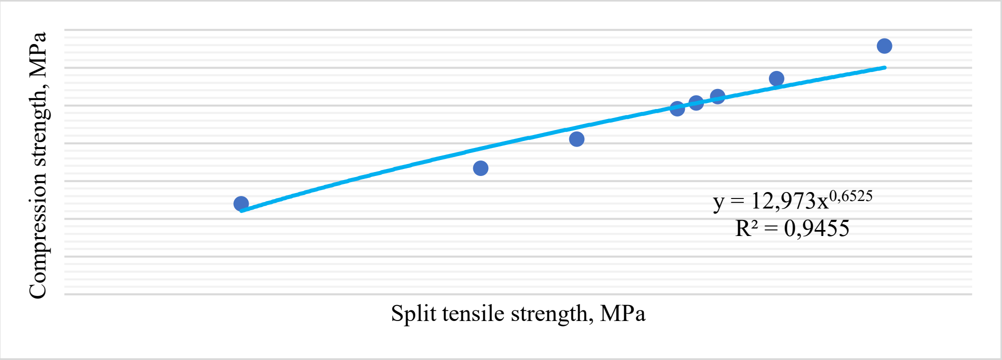

Fig 8. Relationship between split tensile strength and compression strength of SLP20M5 optimal mix

Relationship between optimal flexure strength and optimal compression strength

By statistical analysis, Fig. 9 and 10 show the relationship between split tensile strength and flexure strength of optimal concrete mixes of SLP40M5 and SLP20M5. The correlation coefficients are obtained as R^2=0.9988 and R^2=0.9455 represent good correlation between them. The relation between these two strengths is expressed as y = 5.4221x + 0.2133 and y = 5.0117x + 0.0031, which satisfies the above-mentioned eq. 1 and 2. Out of these, optimal mixes of 1:2:4 and 1:1:2, the SLP20M5 mix of 1:1:2 maintained a good relationship.

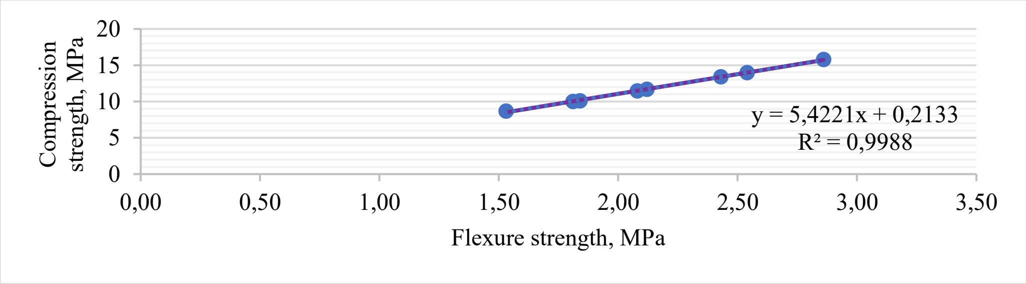

Fig 9. Relationship between flexure strength and compression strength of SLP40M5 optimal mix

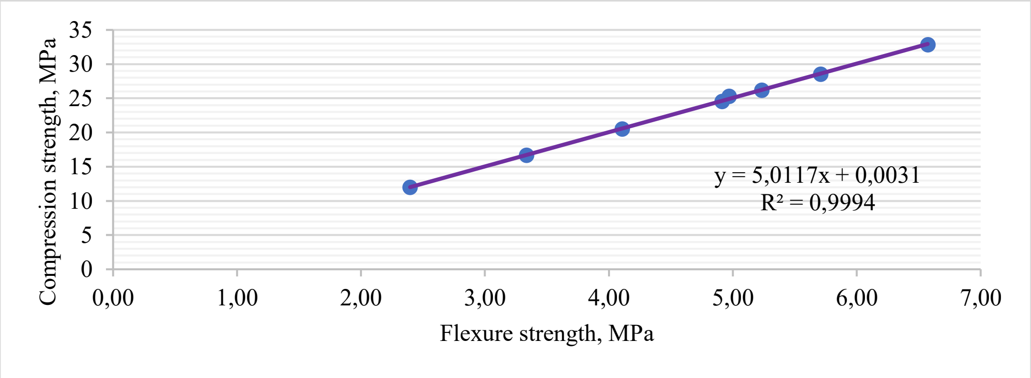

Fig 10. Relationship between flexure strength and compression strength of SLP20M5 optimal mix

6 Recommendations

The present study examines the strength development of lime pozzolana concrete (LPC) prepared using hydraulic lime, fly ash, and sodium silicate gel as cementitious materials. It is also recommended that locally available pozzolans be used as alternatives to these materials to assess the concrete's strength characteristics. Additionally, other chemical activators may be explored to enhance the sustainability of the concrete.

7 Conclusions

The incorporation of sodium silicate gel as a chemical activator significantly enhances the strength of lime-pozzolana concrete (LPC). The pozzolanic reaction between silica, alumina and calcium results in the formation of calcium silicate gel and calcium silicate aluminate gel contributing to strength development [6]. The SLP20 mix, containing 35% hydraulic lime and 25% sodium silicate gel, exhibited superior mechanical strength contrasted to the SLP40 mix with the same proportions, as well as the LP40 and LP20 mixes. This improvement is attributed to the higher concentration of cementitious materials. A higher cementitious material content leads to an increased formation of hydration products, reducing porosity and creating a denser lime-pozzolana concrete structure [26], [27]. Additionally, the use of sodium silicate gel aligns with sustainable construction practices by offering an effective method to reduce greenhouse gas emissions while maintaining structural integrity across various construction applications[28].

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9 References:

- E.R. Grist, K.A. Paine, A. Heath, J. Norman, H. Pinder. (2015) Structural and durability properties of hydraulic lime–pozzolan concretes. Cem. Concr. Compos. 62: 212-223.
- B.A. Silva B.A. Silva, A.P. Ferreira Pinto, Augusto Gomes. (2014) Influence of natural hydraulic lime content on the properties of aerial lime-based mortars. Constr. Build. Mater. 72:208-218.
- E. Ontiveros-Ortega, Esther Ontiveros-Ortega, Reyes Rodrígue Garcia, Ana Gonzalez-Serrano, Lidia Molina. (2018) Evolution of mechanical properties in aerial lime mortars of traditional manufacturing, the relationship between putty and powder lime. Constr. Build. Mater. 191:575-589.
- D. Zhang Dajiang Zhang, Jihui Zhao, Dongmin Wang, Chenyang Xu, Mengyi Zhai, Xia ngdong Ma. (2018) Comparative study on the properties of three hydraulic lime mortar systems: Natural hydraulic lime mortar, cement-aerial lime-based mortar and slag-aerial lime-based mortar. Construction Building Materials. 186:42-52.

- Ana L. Velosa, Paulo B. Cachim. (2009) Hydraulic-lime based concrete: strength development using a pozzolanic addition and different curing conditions. Construction Buildings Materials. 23(5):2107-2111.
- Ramalingam Malathy, Ragav Shanmugam, Deepalakshmi Dhamotharan, Dhivya Kam araj, Mayakrishnan Prabakaran, Jongpil Kim (2023) Lime based concrete and mortar enhanced with pozzolanic materials – State of art. Constr. Build. Mater. 390:131415
- M. Stefanidou, I. Papayianni. (2005) The role of aggregates on the structure and properties of lime mortars Cem. Concr. Compos. 27(9-10):914-919.
- A. Moropoulou, A. Bakolas, P. Moundoulas, E.Aggelakopoulou, S.Anagnostopoulou. (2005) Strength development and lime reaction in mortars for repairing historic masonries. Cem. Concr. Compos. 27(2):289-294.
- P. Faria, Fernando Henriques, Vasco Rato. (2008) Comparative evaluation of lime mortars for architectural conservation. J. Cult. Herit. 9(3):338-346.
- David O. Koteng, Chun-Tao Chenet al. (2015) Strength development of lime-pozzolana pastes with silica fume and fly ash. Constr. Build. Mater. 84:294-300.
- Daniel da Silva Andrade, João Henrique da Silva Rêgo, Paulo Cesar Morais, Moisés Frías Rojas. (2018) Chemical and mechanical characterization of ternary cement pastes containing metakaolin and nanosilica Constr. Build. Mater. 159:18-26.
- P Mira, V.G Papadakis, S Tsimas.(2002) Effect of lime putty addition on structural and durability properties of concrete. Cem. Concr. Res. 32(5): 683-689.
- Masimawati Abdul Latif, Sivakumar Naganathan, Hashim Abdul Razak, Kamal Nasharuddin Mustapha. (2015) Performance of lime kiln dust as cementitious material, 5th International conference of euro Asia civil engineering forum (EACEF-5) Procedia Eng. 125:780-787.
- Marco Franzini, Leonardo Leoni, Marco Lezzerini. (2000) A procedure for determining the chemical composition of binder and aggregate in ancient mortars: Its application to mortars from some medieval buildings in Pisa. J. Cult. Herit.1(4):365-373.
- Nikhil Kumar Degloorkar, Rathish Kumar Pancharathi (2022)Use of particle packing methods for development of lime fly ash-based mortars for repair of heritage structures. Mater. Today: Proc. 61(2):123-131.
- R. Jaafri, A. Aboulayt, S.Y. Alam, E. Roziere, A. Loukili (2019) Natural hydraulic lime for blended cement mortars: Behavior from fresh to hardened states. Cem. Concr. Res. 120: 52-65.
- Peter A. Adesina, Festus A. Olutoge (2019) Structural properties of sustainable concrete developed using rice husk ash and hydrated lime. J. Build. Eng. 25:100804.
- S.A. Barbhuiya, J.K. Gbagbo, M.I. Russell, P.A.M. Basheer (2009) Properties of fly ash concrete modified with hydrated lime and silica fume. Constr. Build. Mater. 23(10):3233-3239.

- V. Nežerka, Z. Slížková, P. Tesárek, T. Plachý, D. Frankeová, V. Petráňová (2014) Comprehensive study on mechanical properties of lime-based pastes with additions of metakaolin and brick dust. Cem. Concr. Res. 64:17-29.
- Ioanna Papayianni, Maria Stefanidou (2006) Strength-porosity relationships in lime-pozzolan mortars Constr. Build. Mater. 20(9):700-705
- K. Mohammed Haneefa, S. Divya Rani, R. Ramasamy, Manu Santhanam. (2019) Microstructure and geochemistry of lime plaster mortar from a heritage structure.Constr. Build. Mater. 225:538-554.
- Stefanidou Maria (2010) Methods for porosity measurement in lime-based mortars Constr. Build. Mater. 24(12):2572-2578
- Xudong Chen, Shengxing Wu, Jikai Zhou (2013) Influence of porosity on compressive and tensile strength of cement mortar. Constr. Build. Mater. 40:869-874.
- A. Izaguirre, J. Lanas, J.I. Álvarez. (2010)Ageing of lime mortars with admixtures: durability and strength assessment. Cem. Concr. Res. 40(7):1081-1095.
- Kuangliang Qian, Yufeng Song, Junying Lai, Xiaoqian Qian, Zhe Zhang, Yong Lian, Sh aoqin Ruan (2022)Characterization of historical mortar from ancient city walls of Xindeng in Fuyang, China. Constr. Build. Mater. 315:125780.
- M. Ghrici, S. Kenai, M. Said-Mansour (2007) Mechanical properties and durability of mortar and concrete containing natural pozzolana and limestone blended cements Cem. Concr. Compos. 29(7):542-549.
- L. Gulbe, I. Vitina, J. Setina (2017) The influence of cement on properties of lime mortar Procedia Eng. 172:325-332.
- J.L. Provis, A. Palomo, C. Shi (2015) Advances in understanding alkali-activated materials. Cement Concr Res. 78:110-125.
- A. Adam, et al. The effect of lime addition on the setting time and strength of ambient cured fly ash based geopolymer binder MATEC Web of Conferences, 47 (2016), Article 01015.
- Sohaib Nazar, Jian Yang, Muhammad Ashraf, Fahid Aslam, Muhammad Faisal Javed, Sayed M. Eldin, Jianhe Xie (2023). Formulation and characterization of cleaner one-part novel fly ash/lime-based alkali-activated material. J. of Mat. Res and Tech. 23:3821-3829.
- Parasa Lakshmi Naga Sroja, B.Vijaya Saradhi (2025).A Comparative Assessment of Mechanical Properties of Lime Pozzolana Concrete Activated by Sodium Silicate Gel. Sou. East. Eur. Jour. of Pub. Heal.26:2952-2958.
- M.S.Shetty, A.K.Jain, Concrete Technology- Theory and Practice, S. Chand Publishers, New Delhi.
- IS 5817:1992- Preparation and use of lime-pozzolana mixture concrete in buildings and roads- code of practice. Bur. Indian Std., New Delhi.
- IS 712:1984- Specification for building lime. Bur. Indian Std., New Delhi
- IS 6932:1973- Methods of tests for building lime. Bur. Indian Std., New Delhi
- IS 3812:2003- Pulverized fuel ash – specification. Bur. Indian Std., New Delhi

- IS 456-2000: Indian Standard Plain and Reinforced Concrete Code of Practice. Bur. Indian Std., New Delhi
- IS:383-1970: Specification for coarse and fine aggregates from natural sources for concrete. Bur. Indian Std., New Delhi
- IS 2386 (part3) - 1963: Methods of test for aggregates for concrete. Bur. Indian Std., New Delhi
- IS 516:2021- Hardened concrete – methods of test. Bur. Indian Std., New Delhi M.S.Shetty, A.K.Jain, Concrete Technology- Theory and Practice, S.Chand Publishers, New Delhi.