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Experimental Investigation of Cement Mortar Incorporating Stone Powder and Admixtures

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Abstract - Concrete is a versatile building material that finds use in many various applications. In typical conditions, it works effectively, but in extreme circumstances, it may fail as well. Admixtures can be added to cementitious materials to achieve the required properties during or after construction. Admixtures that accelerate cement composites' early age strength development and setting happen more quickly. Stone is also a significant building material used in the construction industry. Annually, a significant amount of waste is generated due to the stone industry's expansion and the building sector's growth. Stone wastes have been deposited on valuable land and watersheds in various forms such as slurry, dust/powder, broken slabs, and aggregates. It disturbs the ecology and may cause detrimental effects to the environment as a consequence. In the present investigation, the viability of using stone powder and accelerating admixtures in concrete has been investigated from both an ecological and economical aspect. This study substituted stone slurry powder for cement; non-linear regression equations were also developed, and calcium nitrate and triethanolamine were utilized as additions to examine the applicability of additives in mortar. Additionally, a cost and environmental impact study was carried out. The findings showed that stone powder was more effective in terms of strength, cost, and environmental friendliness. The specimens that were cured in water had a greater compressive strength than air-cured specimens. The optimum percentage of calcium nitrate and stone waste was 1% and 7.5% in the mortar mixes.

***Keywords*:** Stone waste, Strength, Electrical Resistivity, Non-Linear Regression Equations, Micro-Structural characterization, Environmental Assessment

1. Introduction

The present construction industry demands rapid building using cost-effective and environmentally friendly cement composites that offer enhanced strength and durability. Recent research has concentrated on modifying concrete characteristics and creating novel elements to enhance the durability of concrete for speedy construction [1]. Numerous chemical admixtures are commercially accessible for modifying the characteristics of cement-based materials in response to environmental factors. Calcium chloride, a typical set accelerator, leads to corrosion of reinforcing bars. [2]. This issue could be resolved by using chloride-free admixtures in the concrete. Calcium nitrate (CN) is a soluble inorganic compound used as a set accelerating additive with anti-freezing properties [3]. Triethanolamine (TEA) is a chemical utilized as a grinding aid and setting regulator. It possesses distinctive qualities that can either speed up or slow down the process of stiffening based on the amount used [4]. Aggoun et al., 2008 found that combining CN with TEA or TIPA reduced setting time and increased strength in cement paste at all stages of development. Huang et al. 2010 [6] discovered that TEA boosted strength after one day but reduced strength after 3 and 28 days. Ogunbode and Hassan (2011) [7] observed that increases in CN concentration led to a decrease in setting time but an increase in compressive strength (CS) because of the high lime level. Kong et al., 2013 [8] found that the inclusion of TEA (0.03-0.10%) improved the initial strength of cement paste but reduced compressive strength after 3 days. Increased dosages significantly reduced the compressive strength after 28 days. Devi et al., 2018a [9] found that the inclusion of CN, marble powder (MP), and TEA hastened the setting time. MP and TEA reduced CS, but CN enhanced the strength.

India ranks as the third largest country in the world in terms of stone production. Stone waste disposal poses a potential adverse effect on the ecosystem. Stone sludge production rises as stone is utilised in different activities, leading to detrimental effects on the environment in terms of land, water, and air pollution. One way to reduce the negative impact of stone slurry powder is to use it for construction by substituting either cement or aggregates [10-16]. Al-Akhras et al., 2010 [17] found that an increase in burnt stone slurry (BSS) content led to a decrease in setting time and workability, while enhancing the mechanical strength and durability of mortar. Rana et al., 2015 [18] found that using up to 10% marble slurry in concrete is effective.

Research Significance

In the present paper, SSP has been used to replace Portland cement to minimize the environmental pollution caused by stone waste. The chemical additives, such as CN and TEA, accelerating in nature were used. CS of cement mortar with various proportions of CN, TEA, and SSP with water curing (WC) and air curing (AC) conditions was studied at 1, and 7 days. A non-linear regression equation was also proposed for the prediction of CS of mortar at 28 days using curve fitting technique. The ecological and economic aspect of different mixes of mortar were also evaluated. The study aims to investigate the feasibility of using CN, TEA, and SSP in cement mortar under both water and air curing conditions. The goal of using accelerators with stone slurry powder is to produce an environmentally friendly material at an affordable price.

2. Methodology

2.1. Materials and test methods

The study utilised 43 grade Ordinary Portland Cement (OPC) from Binani Cement, an Indian brand, with a fineness of 4 mm, 27.5% consistency, specific gravity of 3.12, and a 28-day strength of 44.5 MPa, meeting the Indian standard code IS:8112-1989. Coarse sand with a fineness modulus of 3.17, falling under zone II, and a specific gravity of 2.62, complying with IS:383-2016, was also used [19-20]. The CN and TEA utilized exhibited accelerating properties. Stone slurry was obtained from Kota, Rajasthan, India [21, 22]. The Kota stone slurry powder is white in colour, with a specific gravity of 2.72, and its main component is calcium. Calcium nitrate tetrahydrate at varying concentrations (0%, 1%, and 2%) and triethanolamine in different concentrations (0%, 0.025%, 0.050%, and 0.1%) were employed as cement additives [22, 23]. Stone slurry powder was utilised as a substitute for cement at 5% and 7.5% proportions. Table 1 provides the chemical composition of cement and stone slurry powder, while figures 1 (a), (b), (c), and (d) display their SEM and EDS images [22].

Table 1: Chemical compound of Portland cement and SSP [21, 22]

Chemical composition (%)	OPC	SSP
CaO	60.29	49.78
SiO_2	21.42	17.01
N_2O	0.64	0.88
MgO	2.65	0.61
Al_2O_3	5.91	2.92
FeO	4.81	0.14
K_2O	1.11	0.42
SO_3	3.17	-

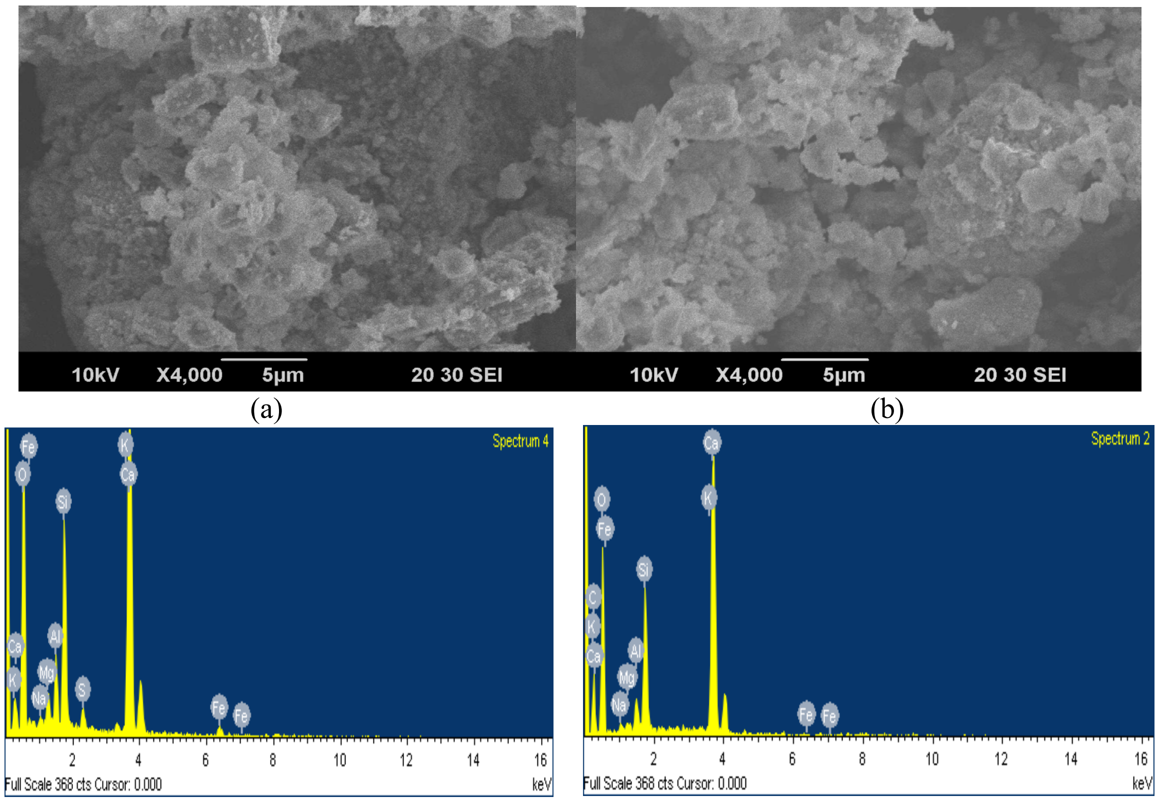

Fig. 1: (a) SEM of OPC; (b) SEM of SSP; (c) EDS of OPC and (d) EDS of SSP

The quantities of cement and sand were 575 kg/m^3 and 1725 kg/m^3 respectively for the plain mix proportions. The mix proportions from trial mixes have been given in table 2.

Table 2: Mix designation of cement mortar

Mix No.		Quantity of materials (%)		
		SSP (%)	CN (%)	TEA (%)
D0	Reference mix	0	0	0
D1	SSP	5	0	0
D2		7.5	0	0
D3	TEA	0	0	0.025
D4		0	0	0.05
D5		0	0	0.1
D6	CN	0	1	0
D7		0	2	0
D8	CN+TEA	0	1	0.025
D9		0	2	0.025

D10	SSP+TEA	5	0	0.05
D11		7.5	0	0.1
D12	SSP+CN	5	1	0
D13		7.5	1	0
D14		5	2	0
D15		7.5	2	0
D16	SSP+CN+TEA	5	1	0.1
D17		7.5	1	0.1
D18		5	2	0.05
D19		7.5	2	0.05

2.2. Compressive strength

An experiment was conducted on the compressive strength of mortar cubes with dimensions of 70.6 mm x 70.6 mm x 70.6 mm, using various mix proportions. The cubes were tested after 1 and 7 days of curing in both air and water, using the guidelines of IS: 4031-1988, Part-6 [24].

2.3. Ecological and Cost analysis

The ecological and economic assessments of plain concrete mix and concrete mix with additives were compared. The study assessed the financial and environmental effects of mortar composed of CN, TEA, and SSP in various proportions [22]. The emission factor values for materials have been sourced from references [25-27]. Embodied energy (EE) and embodied carbon dioxide (ECO_2) refer to the energy and carbon dioxide emissions generated during the production of materials. Flower and Sanjayan (2007) [28] noted that the low amount of EE and ECO_2 per cubic metre (less than $2l/m^3$) in TEA was not considered. The study also evaluated EE, ECO_2, and cost per unit strength [29]. Equation 1 demonstrates the multiplication of the emission factor by the mass of the materials to determine the values of EE, ECO_2, and cost.

$$EE / ECO_2 / Cost = \Sigma g_i m_i \tag{1}$$

Where g_i represents the energy/carbon emission/cost of materials per unit mass and m_i represents the mass of concrete elements 'i' per unit cubic metre

2.4. Performance Index

The Performance Index (PI) tool facilitates the calculation of the SSP content to provide optimal combinations that fulfil the required performance characteristics. Equation 2 was utilised to compute the numerical index (Ri), and the maximum numerical index selected was 5.00 [22].

$$R_i = \frac{\text{Measured performance for each mixture}}{\text{Best measure performance}} \times 5 \tag{2}$$

3. Results and Discussion

3.1. Compressive strength

The variation of CS of all mix proportions of mortar cubes at 1, and 7 days have been shown in fig. 2 (a), (b), (c) and (d) for water and air curing condition respectively. Fig. 2 (a) depicted that CS of different mix proportions varied from 14.14 MPa to 19.85 MPa at 1 day and 22.38 MPa to 38.53MPa at 7 days for water cured specimens. Fig. 2 (a) demonstrates that replacement of cement with SSP improved CS of mortar at all curing ages due to its pore filling effect which formed dense matrix [10, 18]. Addition of TEA significantly increased CS at 1 day and similar results were reported by other researchers [5, 6, 8]; while, decreased the strength at 7 days of curing may be due to its retarding effect on C_3S hydration process [8, 30]. The increase and decrease in strength due to addition of TEA may be because of its accelerating retarding nature depending on its dosages. CN (1%) enhanced the strength of mortar [5, 31]; while at 2%, it reduced the strength. The increase in CS with the addition of CN may be due to better bonding [32]. CN+TEA reduced CS of mortar at all curing ages may be due to predominant nature of TEA; except for D8 at 1 day may be acceleration in hydration process during first 24 hours. 7.5% SSP + 0.1% TEA enhanced CS at 7 days of water curing; but, at 1 day it reduced CS; whereas, 5% SSP+0.05% TEA had vice versa effect. CN+SSP reduced the CS of mortar at all curing ages. 5% SSP had higher CS than that of 7.5% in combination with CN. 1% CN + 0.1% TEA + 5% SSP and 2% CN + 0.05% TEA + 5% SSP enhanced CS of mortar may be because of predominant nature of SSP and CN; while, others combinations i.e. CN+TEA+SSP reduced the CS.

Fig. 2 (b) depicts the percentage increase and decrease in CS of mortar under water curing in comparison to plain mix graphically. The increase in CS with the use of SSP varied from 7% to 11% at 1 day, and 14% to 22% at 7 days with water curing. Addition of CN (1%) increased compressive strength of the order of 1%, and 1% at 1, and 7 days respectively; and decreased at 2% CN by 4%, and 7% with water curing at 1, and 7 days respectively. CS reduced with the addition of TEA from 5% to 16% at 7 days. The combination of TEA, CN, and SSP decreased the compressive strength from 0.1% to 17% at 1 day, and 0.2% to 26% at 7 days. For mix D11, D16 and D18; the compressive strength increased by 19%, 7% and 1% at 7 days.

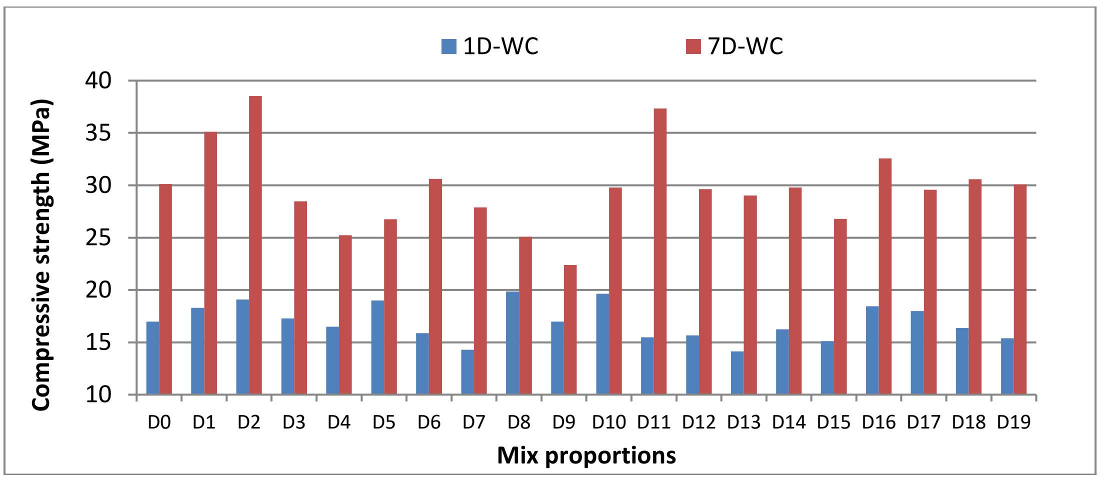

Fig. 2: (a) Compressive strength of mortar under water curing conditions

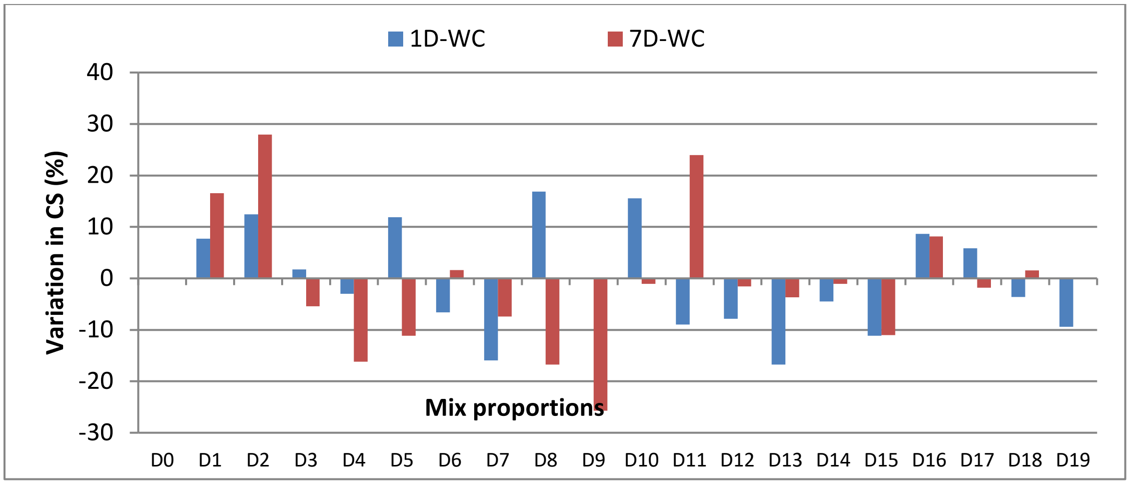

Fig.: 2 (b) Percentage changes in compressive strength under water curing

Fig. 2 (c) showed that CS of air cured specimens of various mix proportions varied from 10.1 MPa to 16.89 day, and 17.56 MPa to 26.84 MPa at 7 days. The inclusion of SSP in mortar increased CS in proportion to plain mix curing ages may be due to filler effect. Addition of TEA increased CS at 1 day may be due to acceleration in hydration process during first day in comparison to reference mix; but reduced at 7 days may be because of retardation of hydration process. CN at 1% increased strength due to better bonding while at 2% reduced the strength of mortar at all curing ages. The combination of CN+TEA reduced the CS of mortar at all curing ages. 1% addition of CN had higher CS than that of 2%. The combination of 7.5% SSP + 0.1% TEA increased CS of mortar may be because of predominant effect of SSP particles; while, 5% SSP + 0.05% TEA reduced CS at 7 days, and increased at 1 day because of acceleration in hydration due to TEA. CN+SSP reduced CS of mortar for all curing ages. CN+SSP+TEA increased CS at 1 day due to presence of accelerators; while, reduced at 7 days except for mixes D16 and D18. D16 and D18 enhanced CS at all curing ages. The increase or decrease in CS with the use of TEA may be because of its accelerating or retarding nature dependant on its dosages.

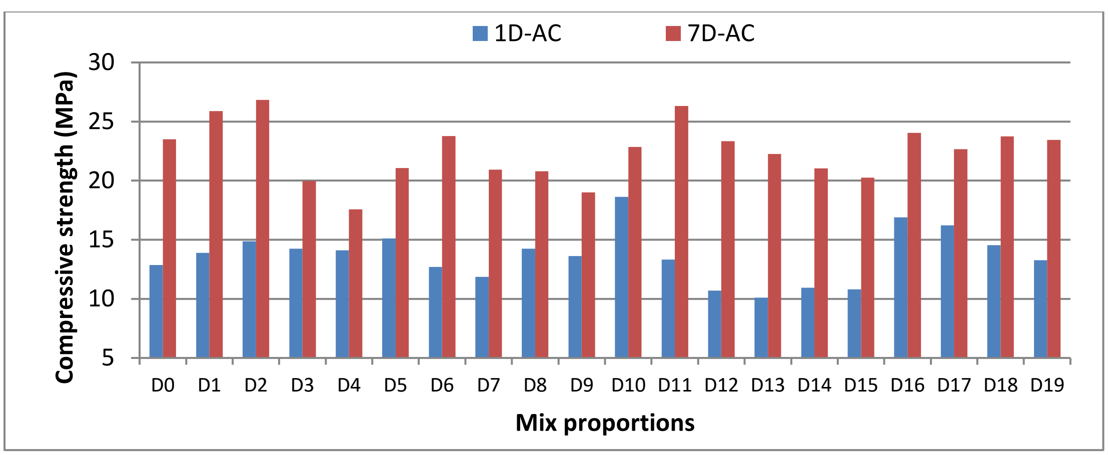

Fig.: 2 (c) Compressive strength of mortar under air curing conditions

The air cured specimens had lower CS than water cured due to insufficient available moisture for the hydration process [33].

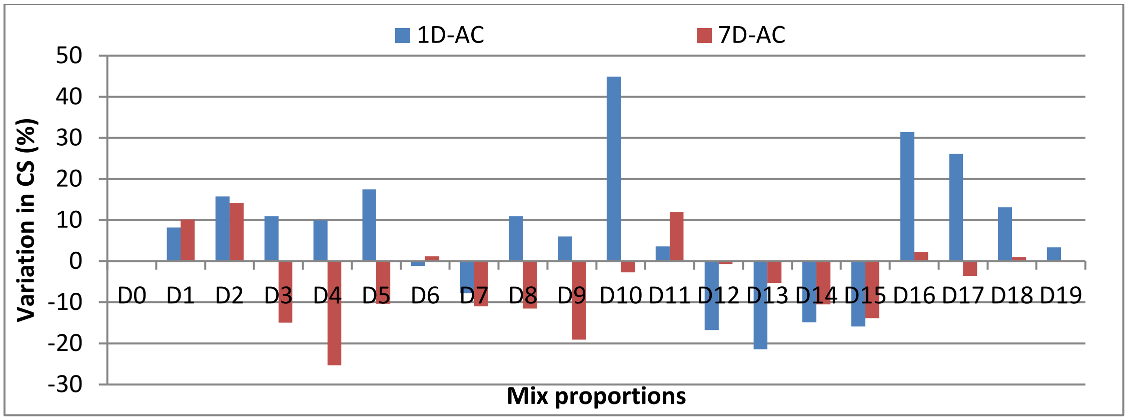

Fig.: 2 (d) Percentage changes in compressive strength under air curing

where D WC = Water curing in days and D AC = Air curing in days

3.2. Ecological and Cost analysis

The study evaluated the embodied energy, embodied carbon dioxide, and cost of various mortar mix amounts, which are presented in a table. EE, ECO2, and cost per unit for 7-day strength under water and air curing conditions were computed and are presented in table 4. The lowest values of EE, ECO2, and cost suggest an environmentally friendly and cost-effective mix proportion, while the highest values imply the opposite. The mix proportion D2, with stone waste at 7.5%, was the most cost-effective and environmentally friendly alternative compared to all other mix proportions.

Table 4: EE, ECO_2 and cost of various mix proportions

Mix No.	Water curing			Air Curing		
	EE/7D-CS	ECO2/7D-CS	Cost/7 D-CS	EE/7D-CS	ECO2/7D-CS	Cost/7 D-CS
D0	97.32	18.05	172	124.74	23.14	221
D1	79.56	14.72	144	107.89	19.97	195
D2	70.71	13.07	129	101.50	18.76	185
D3	102.93	19.09	187	146.71	27.21	267
D4	116.14	21.54	218	166.93	30.96	313
D5	109.50	20.31	217	139.19	25.82	275
D6	95.82	17.86	250	123.35	22.99	322
D7	105.20	19.70	363	140.20	26.25	484
D8	116.96	21.80	311	141.04	26.28	375
D9	131.05	24.54	459	154.20	28.88	540
D10	93.77	17.35	179	122.19	22.61	234
D11	72.98	13.49	150	103.55	19.14	212
D12	94.27	17.53	253	119.71	22.27	322
D13	93.91	17.45	256	122.48	22.76	334
D14	93.82	17.54	335	132.90	24.84	475
D15	101.75	19.00	370	134.61	25.14	489
D16	85.76	15.95	249	116.28	21.63	338

D17	92.16	17.12	272	120.26	22.35	355
D18	91.37	17.08	336	117.73	22.01	434
D19	90.62	16.92	340	116.20	21.70	436

3.3. Performance evaluation of mortar mixes

The individual criteria performance indices of mortar mix proportions as per the desired requirements have been evaluated and given in table 5. In case of cost and ecological aspects i.e. EE and ECO_2, lower value had the best performance and for strength and durability, higher value of R_i was the best mix proportions for the respective property. For individual criteria, if 1 day strength is considered then mix N2 should be preferred. Similarly, if strength under water and air is the selection criteria or the desired requirements, then D2 is the most preferable mix. The mix D2 was selected if low cost, EE and ECO_2 required. As per desired requirement, the mixes with higher R_i can be selected for those particular applications. The highlighted mixes are the optimized mixes.

Table 5: Individual performance indices of mortar

Mix No.	1D WCS	7D WCS	1D-ACS	7D-ACS	28d-WER	28d-AER	EE	ECO_2	Cost
D0	4.28	3.91	3.45	4.38	3.84	4.12	5.00	4.95	2.52
D1	4.61	4.56	3.73	4.82	4.00	4.92	4.76	4.71	2.45
D2	4.81	5.00	3.99	5.00	4.40	5.00	4.64	4.58	2.41
D3	4.35	3.70	3.83	3.72	4.57	4.48	5.00	4.95	2.59
D4	4.15	3.28	3.79	3.27	4.16	4.21	5.00	4.95	2.67
D5	4.79	3.47	4.05	3.92	3.94	3.88	5.00	4.95	2.82
D6	3.75	3.97	3.41	4.43	5.00	4.73	5.00	4.97	3.72
D7	4.10	3.62	3.18	3.90	4.55	4.69	5.00	5.00	4.92
D8	5.00	3.25	3.83	3.87	3.30	3.61	5.00	4.97	3.79
D9	4.28	2.90	3.66	3.54	3.51	3.76	5.00	5.00	4.99
D10	4.94	3.87	5.00	4.26	2.99	3.20	4.76	4.71	2.60
D11	3.90	4.84	3.57	4.90	2.74	3.02	4.64	4.58	2.71
D12	3.44	3.85	2.87	4.35	3.23	3.52	4.76	4.73	3.65
D13	3.81	3.77	2.71	4.14	3.30	3.62	4.65	4.61	3.61
D14	4.03	3.87	2.94	3.92	3.19	3.43	4.76	4.76	4.85
D15	3.78	3.48	2.90	3.77	3.30	3.58	4.65	4.63	4.82
D16	3.62	4.23	4.54	4.48	3.08	3.47	4.76	4.73	3.95
D17	4.38	3.84	4.35	4.22	3.39	3.67	4.65	4.61	3.91
D18	4.65	3.97	3.90	4.42	3.56	3.96	4.76	4.76	5.00
D19	4.53	3.90	3.57	4.37	3.21	3.87	4.65	4.63	4.97

4. Conclusion

This work experimentally investigated the compressive strength and electrical resistivity of several mixtures of cement mortar containing calcium nitrate, triethanolamine, and stone slurry powder under different curing circumstances, such as air and water curing. An exponential equation was created to estimate compressive strength and electrical resistance after air and water curing for 1 and 7 days. The present study yielded the following results:

i. Mortar specimens cured in water exhibited increased compressive strength as a result of having adequate moisture during the hydration process.
ii. The strength of the mortar was increased by 1% at 1 day and 7% to 11% at 7 days with the addition of CN, and by 1% at 7 days and 14% to 22% at 7 days with the addition of SSP. This enhancement is likely a result of improved bonding of solid components in the mortar and the pore-filling impact of stone slurry powder during air and water curing. TEA reduced the mortar's strength by 5% to 16% after 7 days, possibly because it slowed down the hydration process.
iii. The ideal proportions of SSP, CN, and TEA were 7.5%, 1%, and 0.025% of the weight of cement, respectively.
iv. The compressive strength of all mixes reduced when TEA, CN, and SSP were combined, except for D11, D16, and D18, which showed an increase of 19%, 7%, and 1% respectively at 7 days under both air and water curing compared to the control mix.
v. The combination of D1 (5% SSP), D2 (7.5% SSP), and D11 (5% SSP + 0.01% TEA) was proven to be cost-effective and efficient in enhancing strength.
vi. Adding Supplementary Cementitious Materials (SSP) to mortar decreased the Energy Efficiency (EE), Environmental CO_2 emissions (ECO_2), and overall cost of mortar construction, while chemical admixtures increased the cost.

Therefore, stone slurry powder found as environment friendly and cost-effective as well as strength enhancer and durable material. It also reduces the consumption of cement which results in reduction of emission of greenhouse gas upto little extent. Thus, exercise of SSP in cement mortar results in economical and sustainable product. Also, utilization of stone slurry in cement-based materials resolved problems regarding safe disposal of stone slurry. The use of SSP in mortar was feasible and finds many field applications.

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