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Performance assessment of concrete incorporating admixtures and stone waste powder

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The construction industry can use various industrial by-products as raw materials, including wastes from the stone glazing industry, thermal power plants, steel, and rubber sectors. Although the stone industry significantly contributes to the construction industry,it has some limitations regarding landfill disposal of slurry and dust from waste. Accelerators increase the rate of stiffening and hardening, which increases early strength and allows early striking and de-molding of outer formworks, which helps speed up the construction work. In the present investigation, properties such as slump, mechanical, chemical resistance, and microstructural characteristics of concrete specimens were investigated using calcium nitrate (1%), triethanolamine (0.05%), and stone waste powder (10%) alone and in combination. The ecological and economic analysis of concrete was also carried out along with performance evaluation. Results showed that when used separately in the concrete mixture, stone waste powder, calcium nitrate, and triethanolamine enhanced the performance, but their combination declined. Stone waste powder was an economical and eco-friendly concrete material.

Keywords: Stone waste, Chemical additives, Strength, Micro-structural characterization, Ecological and economic analysis, Performance evaluation

1 Introduction

The consumption of cement-based products is increasing dramatically each daydue to infrastructure expansion. This leads to environmental harassment as the construction industry is responsible for greenhouse gases and the depletion of natural resources. This situation demands finding alternatives to raw materials in concrete production to make it economical and eco-friendly[1]. Thus, the awareness of the impact of construction materials on the environment is increased to conserve it.

India has a broad spectrum of dimensional stones. In India, about 90% of marble stone, sandstone, and Kota stone are being produced by Rajasthan. India produces over 85600 million tons of calcareous stone annually and over 185 million tons of all-dimensional stones. During the stone cutting and polishing process, about 17.8 million tonnes of solid calcareous waste is generated annually, along with accumulated waste of 250 million tonnes. The production of Kota stone, a calcareous sedimentary rock, is around 80 lakh metric tonnes (MT) per year. As a byproduct of its mining and processing, 12 lakh MT of fine dust waste is produced annually, of which about 4-5 lakh MT of dust is disposed in the mining area, and the rest is discharged into the conventional area[2]. This sort of disposal affects 5-10 hectares of valuable land annually, and adequate land has already been ruined[2]. The stone-cutting industries produce waste during the mining and polishing process of stones, generally in two forms: solid (generated during extraction) and waste (during the transformation process). Tonnes of stone waste are generated annually; almost 25% of stone goes to waste during the cutting and processing of stone. The disposal of stone waste has become a prime environmental issue globally. There were lots of problems regarding the place for storage and deposition of these wastes. Dumping waste into rivers and lagoons creates an ecological issue andlandfilling has serious drawbacks. The water content is reduced and becomes dust, causing air pollution in industrial areas and adjacent urban areas if dumped on land areas. When it is disposed of on a riverbed, it causes a reduction in the porosity of topsoil, which ultimately reduces soil fertility. A huge amount of money is also spent on transportation. The transportation and dumping of waste embrace additionalcosts, thereby it becomes necessary to incorporate stone waste into the

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*Corresponding author (E-mail: kiranbimbhra@gmail.com) industrial process, which can reduce the management cost and come with new business opportunities. Using stone waste in concrete reduces production costs, saves natural resources and energy, and provides concrete with better properties anda safer environment by resolving its disposal problem[2-5]. Concrete production is feasible and economical, but some improvement is still required to make it more economical and sustainable by utilizing locally available industrial wastes[6]. Replacement of stone waste by 5% with sand enhanced mechanical properties[7]. Cement replacement with granite sludge up to 10% can be efficiently used without loss of compressive strength[5]. Mechanical strength decreased with marble slurry (MS) content[8]. Slump decreased,and mechanical strength increased with MS. It reduced the environmental impact too[9].

Accelerators alter the various properties of concrete, especially in cold weather concreting. Accelerators can be added in grout, mortar, or concrete to accelerate the hydration rate of hydraulic cement. Accelerators are classified depending on their performance and applications (a) Set accelerating admixtures to accelerate setting time and (b) hardening accelerators to enhance the early age strength and usually used where early stripping of shuttering or early access to the structure/pavement is desired. Calcium chloride is commonly used as a chloride-based accelerating admixture in concrete, especially for non-reinforced concrete due to its corrosive nature. Besideschloride-based accelerators, non-chloride and anti-corrosive accelerators i.e., nitrate, nitrite, and amines, are used to accelerate the properties of concrete[10-14]. Triethanolamine (TEA) jeopardized early-age strength[15-16]. Calcium nitrate (CN) positively affected strength[17].

The rapid growth of the stone industry produces a large amount of waste, which damages the environment. Incorporating stone waste powder (SWP) into concrete significantly contributes to the environment and economic feasibility and resolves their dumping problem. This study used CN and TEA as cement additives and industrial by-products i.e., SWP as cement substitution, to examine their effect on the workability, mechanical strength, durability, and micro-structural properties. Also, economic and ecological analysis of concrete mixes,along with the performance index was evaluated. The study aimed to examine the practicality of these additives individually and in various aspects of a blended system in concrete mixtures. The purpose of combining SWP with accelerators is to reduce cement usage and its harmful environmental impact, producing sustainable and economical concrete.

2 Materials and Methods

2.1 Materials

In the present work, country made OPC of 43 gradecomplying with IS: 8112-1989[18,] and its chemical composition has been given in Table 1[1,19]. The scanning electron microscopy (SEM) micrographs and energy dispersive X-ray spectroscopy (EDS) image of cement have been illustrated in Fig. 1 (a &b), and coarse sand of zone II and coarse aggregates of size 10 mm and 20 mm complying with IS: 383-2016[20] were used to prepare concrete mix[22-22]. The chemical composition of stone waste powder is given in Table 1, and its SEM and EDS images are illustrated in Fig. 1 (c & d)[1]. SEM micrographs showed that SWP had more even-shaped particles and finer particle sizes than cement. According to EDS findings, the chemical composition of cement and SSP is comparatively similar. SSP was calcite in nature and it contributed to binding abilities by interacting with tricalcium aluminate (C_3A) to generate calcium carbon aluminate[19]. Two accelerating admixtures, i.e., calcium nitrate tetrahydrate purified with $Ca(NO_3)_2.4H_2O$ and triethanolamine LR with chemical formula $C_6H_{15}NO_3$,were used as additives. Concrete was produced with Glenium SKY 8233 superplasticizer, which is low in alkali and free of chloride.

2.2 Specimens preparation

SWP replaced cement by 10%, CN and TEA were used as additives, with 1% and 0.05%, respectively, according to the weight of cement. Different eight mix proportions were prepared, designed as per IS:10262-2009[23],and designated in Table 2. The cement, sand, coarse aggregates, and water were 440 kg/m^3, 770 kg/m^3, 1055 kg/m^{3,} and 131 kg/m^{3,} respectively, and dosages for various mix proportions have been designated in Table 2. The superplasticizer dose was kept constant at 1%. Casting and testing of the different mixes were carried out as per IS: 516-1959[24].

Table 1 — Chemical compound of OPC and SWP[1, 19]

Chemical compound (%)	CaO	SiO_2	Al_2O_3	FeO	N_2O	K_2O
Cement	60.29	21.42	5.91	4.81	0.64	1.11
SWP	49.78	17.01	2.92	0.14	0.88	0.42

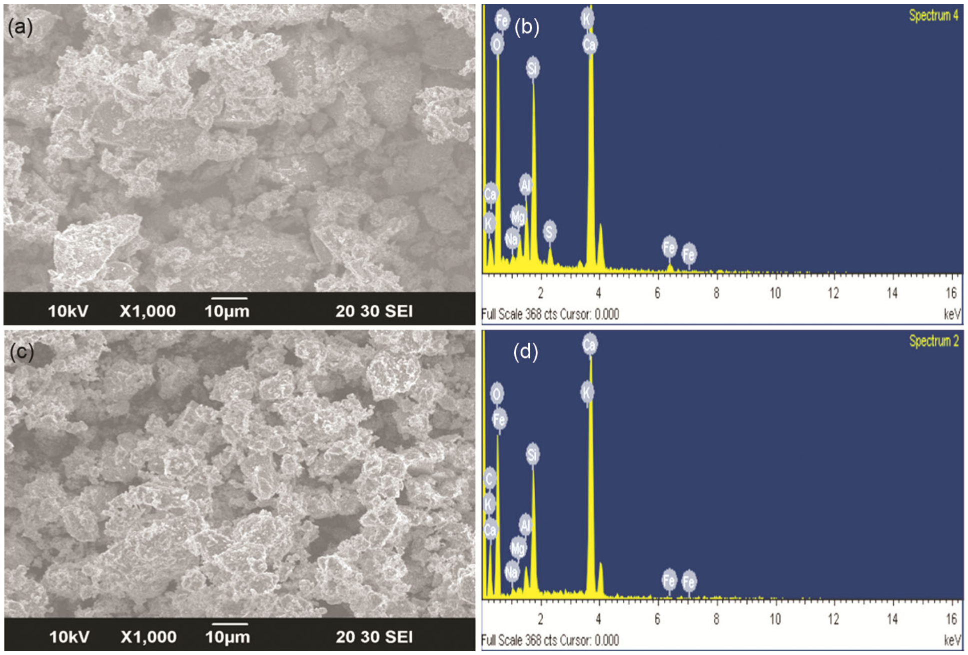

Fig. 1 — (a) SEM of portland cement, (b) EDS of portland cement, (c) SEM of SWP, and (d) EDS of SWP.

Table 2 — Mix designation of various concrete mixtures.

Mix No.	SWP (%)	CN (%)	TEA (%)
K1	0	0	0
K2	10	0	0
K3	0	0	0.05
K4	0	1	0
K5	0	1	0.05
K6	10	0	0.05
K7	10	1	0
K8	10	1	0.05

2.3 Test procedure

The workability of different mix proportions was measured by slump tests as per IS: 1199-1959[25]. The strength properties of various mixtures were investigated at 7 and 28 days as per IS: 516-1959[24]. The concrete cubes (150 mm x 150 mm x 150 mm); and cylinders (150 mm x 300 mm) were used to determine CS, ER; and STS of concrete, respectively. The elastic modulus of concrete specimens was determined using ultrasonic pulse velocity (UPV) values[26]. Dynamic modulus of elasticity, E_d can be determined from pulse velocity using equation (1) given below

$$E_d = \frac{V_p{}^2 \rho (1+\nu)(1-2\nu)}{(1-\nu)} \quad \dots (1)$$

Where V_p=Pulse velocity (m/s); ρ = Density (kg/m^3) and ν= Poisson's ratio of concrete

ER of concrete indicates how easily ions can move inside the specimen. Resistivity can be used to predict durability and corrosion. It can be used for onsite quality control checks as it is a non-destructive test. The electrical resistivity of concrete was measured using two-point probe method[1]. The recommended values for the correlation between electrical resistivity (ER) and corrosion may be taken as given in Table 3.

Table 3 — Co-relation between ER and corrosion intensity[27].

Electrical resistivity (kΩ-cm)	>20	10-20	5-10	<5
Corrosion intensity	Low	Low to Moderate	High	Very high

Table 4 — EE, ECO_2 and cost of raw materials[19]

Materials	Cement	Sand	Water	SWP	CN	SP
EE, MJ/kg	4.8	0.081	0.2	-	-	11.5
ECO_2, $kgCO_2$/kg	0.93	0.0051	0.0008	-	-	0.6
Cost, INR	6	1	0.05	-	-	200

The chemical resistance of concrete specimens was studied at 28# and 62# days after 28* days of water curing (*indicate water cured specimens for 28 days and # indicate specimens under chemical solution at respective ages-confirmingASTM C1012[28].

The microstructural analysis of concrete with different mix proportions was done using SEM and EDS techniques. The cost analysis of concrete with additives was examined and contrasted with the plain concrete mix in terms of its ecological (embodied energy [EE] and embodied carbon dioxide [ECO_2]) and economic impacts. Table 4 contains the values for each material's emission factor, referred from the literature[29–30]. The value of EE, and ECO_2 for TEA was not considered due to their low content per cubic meter (less than 2 l/m^3), as suggested by Flower and Sanjayan[1]. EE, ECO_2, and cost per unit strength were also evaluated[19, 31].

Quantitative analysis of different concrete mixtures was evaluated[19, 32]. The relation between CS and STS, CS and ER of concrete was derived at various ages and compared with the previous studies. The Pearson linear correlation factor was determined, and values near unity indicate a strong linear correlation[33]. The range of correlation factors has been given in Table 5.

3 Results and Discussion

3.1 Workability

The slump for different mix proportions has been illustrated in Fig. 2. The workability decreased due to the addition of finer particles of SSP for mix K2[3, 7]. The incorporation of accelerators decreased the slump due to the low plasticity maintaining effect compared to the control mix, but, higher than SWP. CN had a higher loss in workability than TEA due to the high plasticity-maintaining effect in fresh concrete. The slump value varied from 50 mm to 120 mm. It has been observed from Fig. 2 that the slump value decreased for all the mix proportions and varied from 8.3% to 58.3% for all the mix proportions.

3.2 Compressive strength

Figure 3 shows the influence of SWP and accelerators on CS at various curing ages. The inclusion of CN, TEA, and SWP as cement substitutes each improved the CS of concrete in comparison to plain mix at all curing ages, as shown in Fig. 3. The combination of CN+TEA also enhanced the CS of concrete at 7 and 28 days; while, CN+SWP, TEA+SWP, and CN+TEA+SWP decreased CS of the

Table 5 — Criteria for Pearson linear correlation factor.

Pearson linear correlation factor	<0.2	0.2-0.4	0.4-0.7	0.7-0.9	>0.9
Correlation	No linear correlation	Weak	Moderate	Quite strong	Very strong

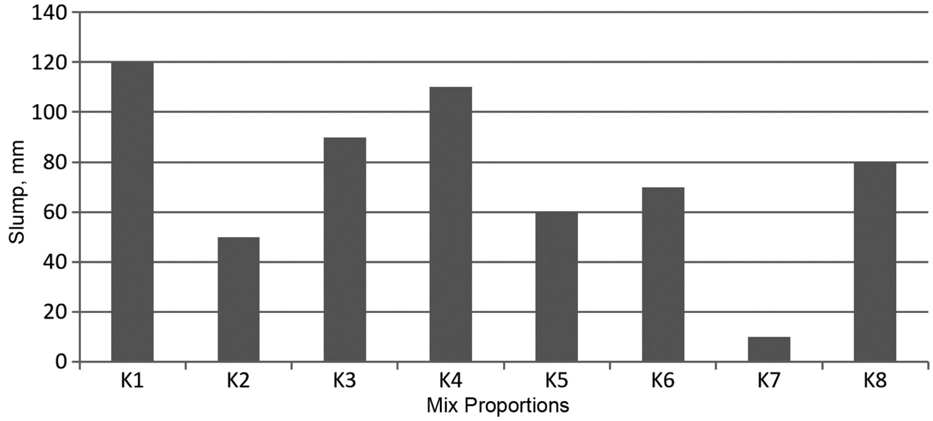

Fig. 2 — Variation of slump of different concrete mixtures.

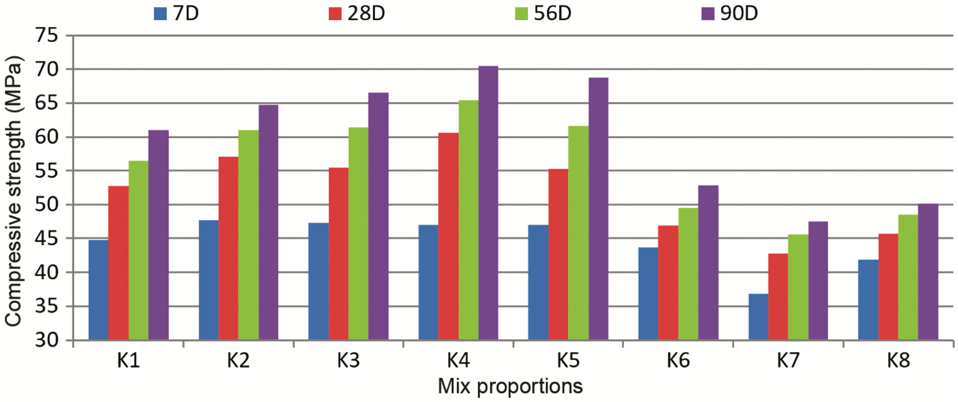

Fig. 3 — Variation of compressive strength of concrete.

concrete compared to control mix at all curing age. Fig. 3 illustrates that SWP increased CS because of the formation of additional hydrated calcium silicate gel due to the reaction of lime with silica[34]. Due to its pore-filling action, which creates an ideal nucleus for hydration and catalyzes the hydration and the water-reducing impact of superplasticizer, SWP enhances the compressive strength of concrete. The results were in good accord with Ergun 2011[35]. CN individually increased CS of concrete[10, 36,]and the increase may be attributed to good bonding between the constituents of the solid phase of concrete[17]. Both alone and in combination, acceleratorsboostedconcrete strength due to improved cement hydration and reduced porosity[37]. CN increased the strength, which may be because of dense aggregates/paste interface or a change in morphology leading to small Ca(OH)2 crystals. CN+SWP reduced the strength because of the reduction in cement quantity as SWP replaced cement. The results of the accelerators and SWP agreed with those of the previous study.

CS of different mixes varied from 36.86 to 47.76 MPa at 7 days, 42.77 to 60.65 MPa at 28 days, 45.58 to 65.44MPa at 56 days, and 50.17 to 70.45 MPa at 90 days, respectively. For K2, K3, K4, and K5, CS of concrete enhanced by 6.2%, 5.32%, 4.6%, and 4.6% at 7 days, 7.6%, 4.9%, 13%, and 4.47% at 28 days, 7.3%, 8.0%, 13.6% and 8.3% at 56 days; and 5.9%, 8.3%, 13.3% and 11.4% at 90 days in proportion to plain mix. For mixes K6, K7, and K8; CS decreased by 2.5%, 17.8%, and 6.6% at 7 days, 11.02%, 19%, and 13.4% at 28 days, 12.33%, 19.4% and 14.2% at 56 days; and 13.4%, 22.04% and 17.7% at 90 days with respect to control mix. The mix K4 had maximum strength; whereas K7 had the lowest strength among all mix proportions.

The comparative analysis of the previous studies with present study for the compressive strength of concrete consisting of stone waste powder as cement substitution by different proportions at 7, 28, 56 and 90 days has been shown in Fig. 4 (a), (b), (c), (d) respectively. The previous studies conducted by Omar *et al.*[38]; Aliabdo *et al.*[39]; Mashaly *et al.*[40]; Singh *et al.*[41]; Ghorbani *et al.*[42,] and Vardhan *et al.*[43] was in good agreement with the present study, and optimum content was 10-15% as shown in Fig. 4. Bacarji *et al.*[44] and Khodabakhshian *et al.*[45] reported that stonepowder at 5% enhanced the CS of concrete.

3. 3 Split tensile strength

STS was studied experimentally with CN, TEA, and SWP at 7 and 28 days of curing and has been depicted in Fig. 5. Figure 5 showed that STS enhanced with the

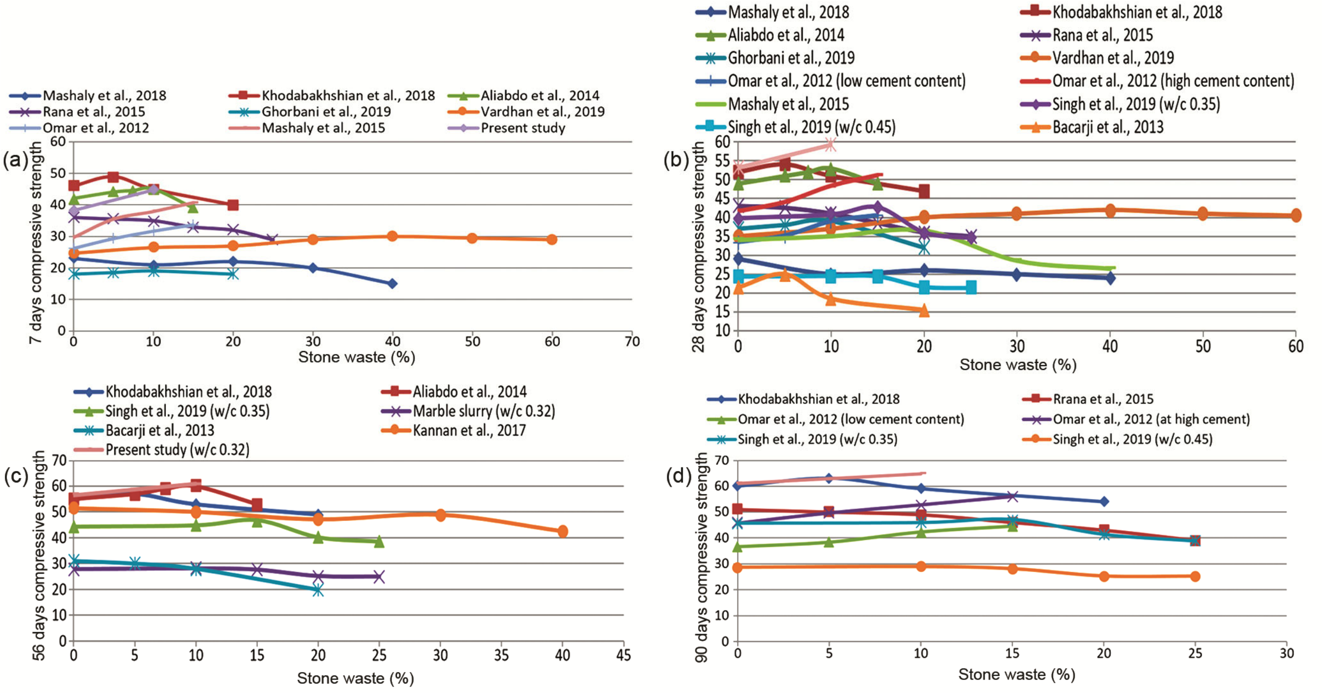

Fig. 4 — Comparison of CS of concrete between present and other studies (a) CS at 7 days, (b) CS at 28 days, (c) CS at 56 days, and (d) CS at 90 days.

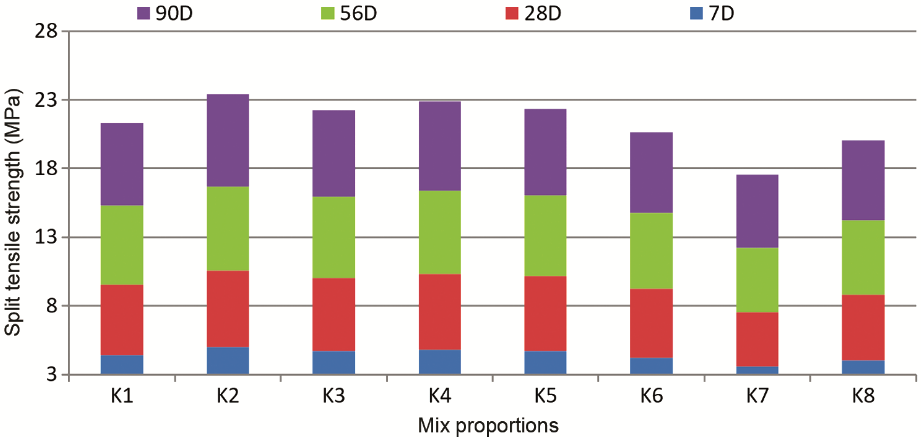

Fig. 5 — Variation in split tensile strength of concrete mixtures.

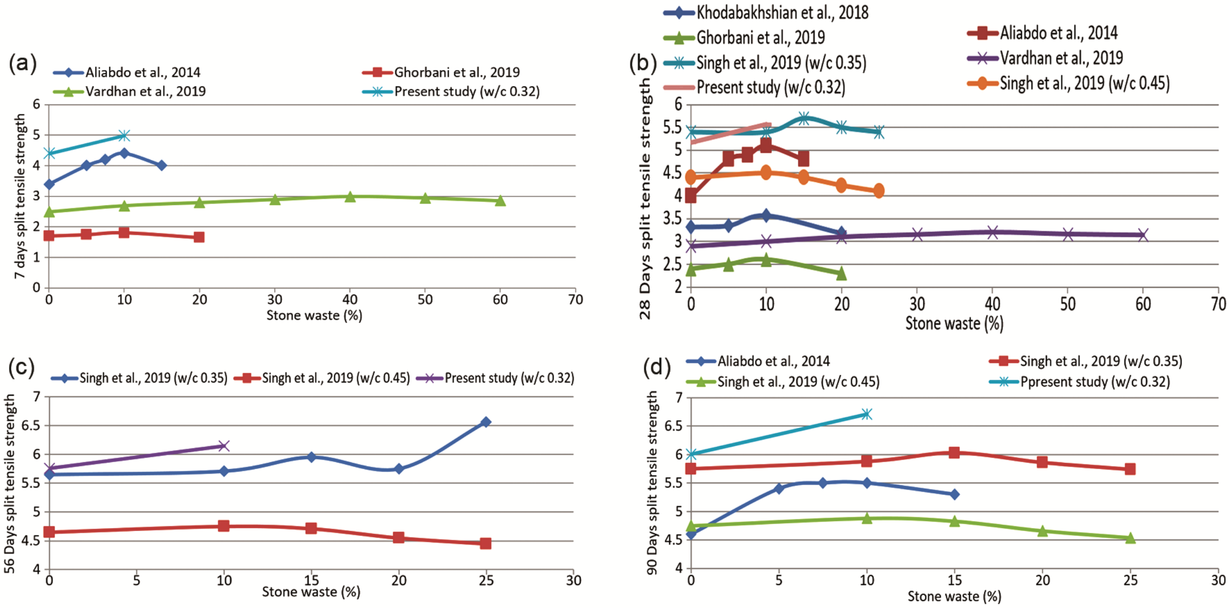

Fig. 6 — Comparison of present study and previous studies for (a) STS at 7 days, (b) STS at 28 days, (c) STS at 56 days, and (d) STS at 90 days.

inclusion of CN, TEA, and SWP separately; but their combination reduced it at all curing ages. SWP increased STS of concrete due to low porosity and good strength of cement paste and interfacial transition zone[45]. Accelerators enhanced STS due to a reduction in porosity, as discussed earlier. The comparison for STS of concrete containing stone powder either from marble or granite stone of the present study with the previous studies at 7, 28, 56, and 90 days has been shown in Fig. 6 (a), (b), (c), (d) respectively. The previous studies by Aliabdo *et al.*[14]; Khodabakhshian *et al.*[45]; Ghorbani *et al.*[42]; Singh *et al.*[41], and Vardhan *et al.*[43]were in good agreement with the results of the present study as shown in Fig. 6.

STS of concrete mixtures varied from 3.58MPa to 4.98MPa at 7 days, 3.94MPa to 5.57MPa at 28 days, 4.72MPa to 6.15MPa at 56 days, and 5.34MPa to 6.71MPa at 90 days curing respectively. STS of mix K2, K3, K4, and K5 increased by 11.6%, 6.2%, 8.5%, and 6.6% at 7 days; 7.2%, 3.5%, 6.2% and 5.5% at 28 days, 6.3%, 2.7%, 5.1% and 2.04% at 56 days; and 10.4%, 4.3%, 7.4% and 4.5% at 90 days curing in comparison to K1. For mix K6, K7, and K8; STS reduced by 3.9%, 18.6% and 8% at 7 days, 2.5%, 23.8%, and 7.9% at 28 days, 4.2%, 18.1% and 5.4% at 56 days; and 2.8%, 11.1% and 4% at 90 days as compared to plain mix. The optimum mix proportion for the split tensile strength was K2.

3.4 Elastic modulus

The elastic modulus of distinct mixtures of concrete consisting of CN, TEA, and SWP was determined from the ultrasonic pulse velocity test and shown in Fig. 7. The elastic modulus followed a similar trend as CS. CN, TEA, SWP, and (TEA+CN) increased the elastic modulus. Combining these materials i.e. CN+SWP, TEA+SWP, and CN+TEA+SWP decreased the elastic modulus. SWP increased the elastic modulus of concrete[7, 45]. The increase in modulus of elasticity indicates the lesser deformation for the same stress when loaded[46].

The value of elastic modulus varies from 42.50 GPa to 51.27 GPa for all the mix proportions. For mix proportions K2, K3, K4, and K5; the elastic modulus increased by 3%, 2%, 8%, and 0.13 % at 28 days; while, mix K6, K7, and K8; decreased the elastic modulus by 3%, 6% and 10% with reference to the control mix. The mix K4 had the maximum value for elastic modulus among all the mix proportions.

3.5 Electrical resistivity

The influence of CN, TEA, and SWP on the ER was studied at 28 days and illustrated in Fig. 8. Figure 8 depicted that ER of the concrete increased for mix K1-K5 but, reduced for mix K6-K8 at 28 days with references to the control mix. An increase in ER may be because the fraction of internal hydration products increased with the strength gain and these hydration products obstruct the path of movement of ions, which ultimately increases the electrical resistivity[47]. Accelerators increased the ER of concrete[48].

ER of concrete varied from 24.83 to 38.7 kΩ-cm at 28 days, 28.53 kΩ-cm to 42.2 kΩ-cm at 56 days, and 30.13 kΩ-cm to 46.2 kΩ-cm at 90 days for all mix proportions. For mix K2, K3, K4, and K5; electrical resistivity increased by 10.2%, 2.3%, 16% and 9.42% at 28 days, 8.5%, 2.9%, 13.5% and 5.1% at 56 days; and 7.7%, 2.6%, 12.4% and 4.6% at 90 days and for mix K6, K7, and K8; electrical resistivity decreased by 23.6%, 12.3% and 18.3% at 28 days, 21.9%, 13% and 18% at 56 days; and 25.6%, 19.5% and 24.6% at 90 days as compared to K1.

The maximum electrical resistivity was for mix K4, which had a low corrosion rate due to the corrosion inhibitor in nature, and the lowest value for mix K8,

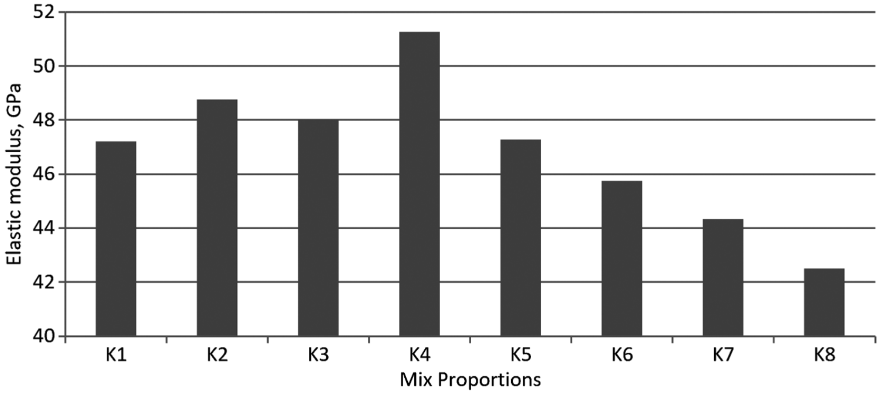

Fig. 7 — Elastic modulus of different concrete mixes at 28 days.

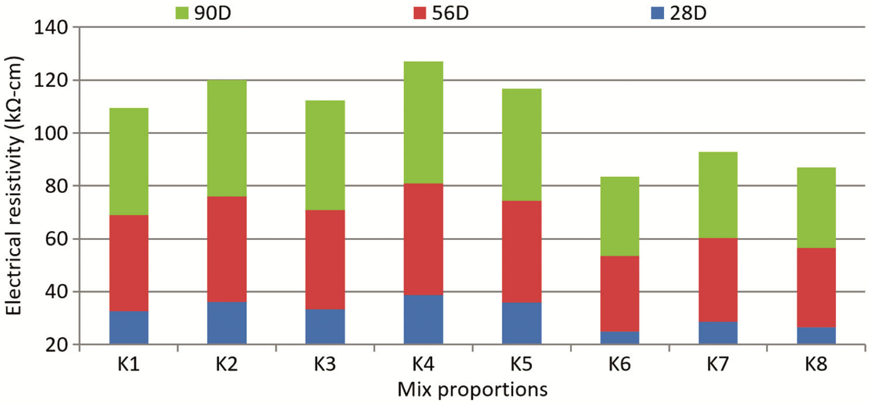

Fig. 8 — Electrical resistivity of different concrete mixtures.

which was more susceptible to corrosion among all the mix proportions, as observed in table 4. The results correspond to Broomfield[27,] which shows that the corrosion rate will be very low if steel reinforcement is provided at any level of construction.

3.6 Durability properties

The concrete cube specimens of different mix proportions were subjected to the exposure of magnesium sulphate (S) solution for 28# and 62# days after 28 days of water curing and variations in CS and ER of concrete were evaluated.

3.6.1 Compressive strength

The influence of chemical attack on CS of concrete containing CN, TEA, and SWP was studied at 28# and 62# days and has been shown in Fig. 9. CS against sulphate attack varied from 40.09MPa to 60.75MPa at 28# days and 36.92MPa to 58.24MPa at 62# days. The strength of mix K4 increased against sulphate solution attack by 10.26 % and 10.49% at 28# and 62# days, respectively. For mix K2, K3, K5, K6, K7, and K8; CS decreased by 3.8%, 2.3%, 0.7%, 20.8%, 26.5%, and 24% at 28 #days; and 9.3%, 3.9%, 1.0%, 24.8%, 29.2% and 25.6% at 62# days exposure to sulphate solution in comparison to plain mix.

Results showed that CS diminished by 3.8%, 2.3%, 0.7%, 20.8%, 26.5%, and 24% at 28 #days; and 9.3%, 3.9%, 1.0%, 24.8%, 29.2% and 25.6% at 62# days for K2, K3, K5, K6, K7, and K8 respectively and for K4 enhanced by 10.26% and 10.49% at 28# and 62# days respectively against sulphate attack. Reduction in CS under sulphate attack may be attributed to the transformation of calcium silicate hydrate (C-S-H) to magnesium silicate hydrate (M-S-H), which destroyed the cement paste[49]. The increment in CS of specimens exposed to sulphate solution attack may be due to ettringite forming a more closed pore structure and enhancing CS[50]. CN improved the resistance due to good bonding, which restrained the penetration of sulphateions.

3.6.2 Electrical resistivity

The effect of additives on ER against magnesium sulphate solution at 28# and 62# days was investigated. The variation in ER of concrete due to chemical attack has been given in Fig. 10 and it has

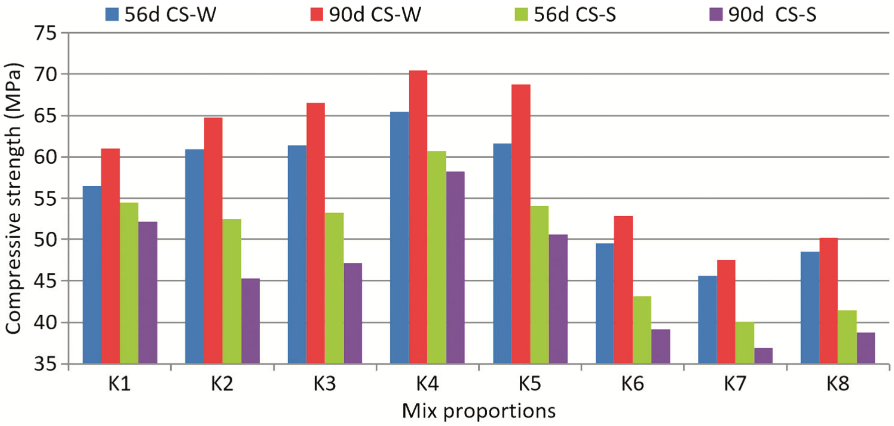

Fig. 9 — Compressive strength of concrete against chemical attack.

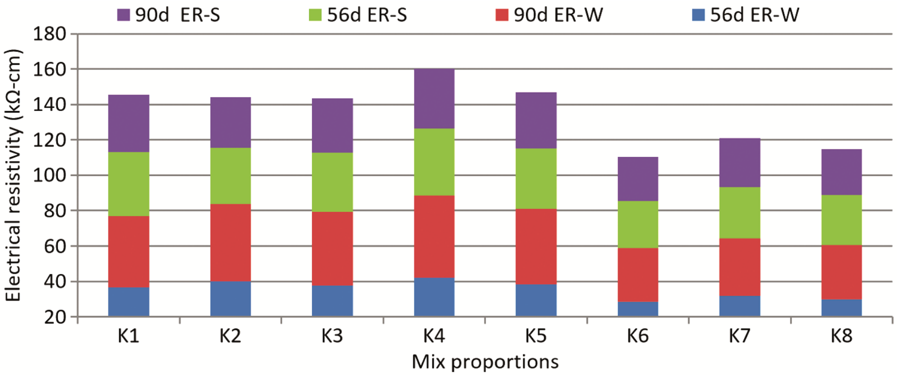

Fig. 10 — Electrical resistivity of concrete specimens subjected to chemical attack.

been observed that ER decreased for all mixes except K4 under exposure to the sulphate attack. CN increased ER due to good bonding of constituents of solid phase in concrete. ER varied from 26.78kΩ-cm to 37.85 kΩ-cm and 24.85 kΩ-cm to 34.12kΩ-cm at $28^{\#}$ days and $62^{\#}$ days for all mix proportions against sulphate attack. The mix proportion K4 increased ER by 4.94% and 4.8% at $28^{\#}$ and $62^{\#}$ days respectively. For mix K2, K3, K5, K6, K7, and K8; ER reduced by 3.2%, 7%, 4.8%, 25.6%, 19.3%, and 20.8% at $28^{\#}$ days; and 3.1%, 5.32%, 2.46%, 23.49%, 15.5% and 19.8% at $62^{\#}$ days exposure to sulphate solution in comparison to plain mix.

The values of ER of concrete under the exposure of sulphate attack were higher than those recommended by Broomfield[27], showing that corrosion was very low for all the concrete mix proportions.

3.7 Micro-structural analysis

SEM and EDS techniques studied the micro-structural characterization of concrete's specimens. Figures 11 (a-p) shows the SEM micrographs and EDS images of different concrete mix proportions. The presence of hydration products i.e., calcium silicate hydrate (CSH), calcium hydroxide (CH), and ettringite can be seen from the SEM micrographs. The presence of silica (Si) can be seen from EDS images of mixes K2, K3, and K5, which react with calcium and form CSH, enhancing the strength and electrical resistivity and dense matrix compared to the control mix. The mix K4 has Ca and Si as major elements and aluminum (Al), contributing to the hydration process and strength development. For mixes K6, K7, and K8, the major element was calcium (Ca), which formed calcium hydroxide and low contribution to CSH gel formation and strength enhancement compared to other mixes. The same findings were reported from the experimental results. Also, mixes K2, K3, K4, and K5 formed the dense matrix as observed from SEM micrographs.

EDS analysis of specimens of concrete with various mix proportions was carried out. As observed

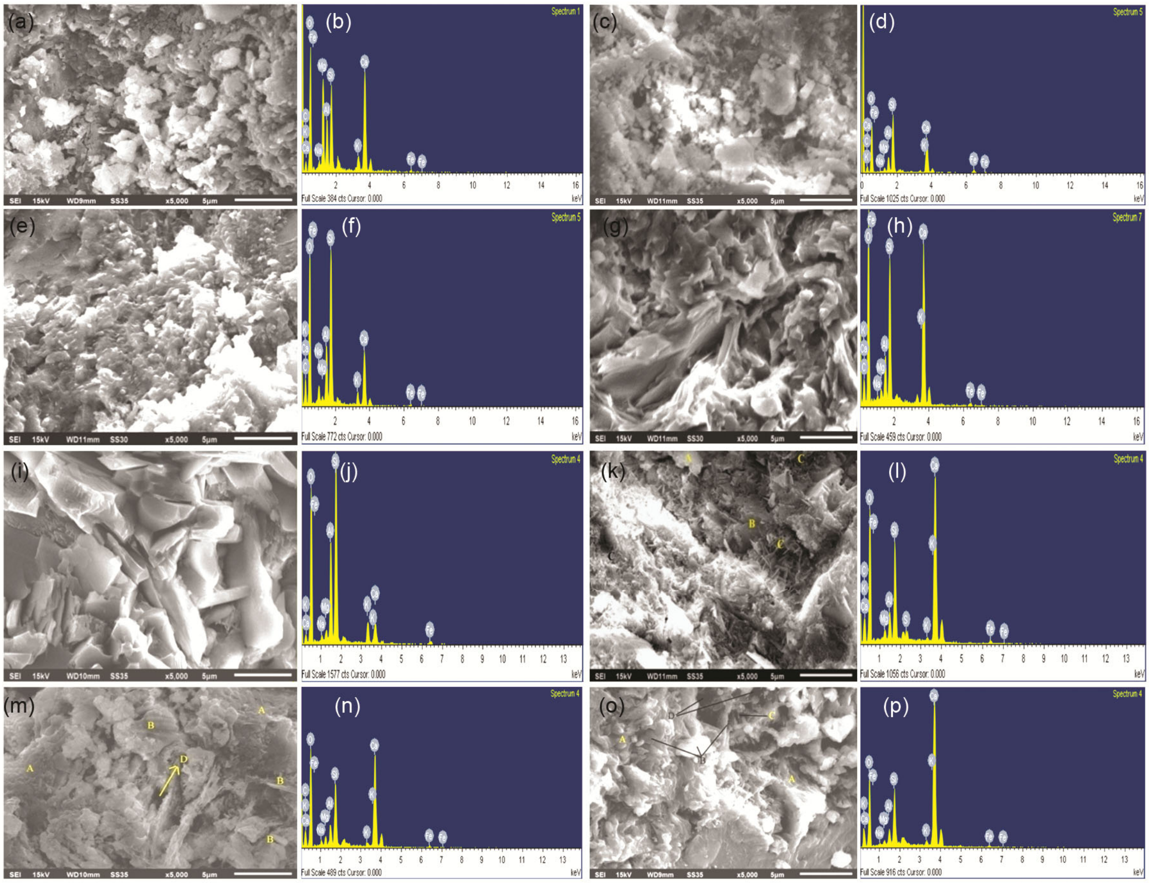

Fig. 11 — (a) SEM of K1, (b) EDS images of K1, (c) SEM of K2, (d) EDS images of K2, (e) SEM of K3, (f) EDS images of K3, (g) SEM of K4, (h) EDS images of K4, (i) SEM of K5, (j) EDS images of K5, (k) SEM of K6, (l) EDS images of K6, (m) SEM of K7, (n) EDS images of K7, (o) SEM of K8, 11, and (p) EDS images of K8.

from Table 6 recommended by Mohammed *et al.*[51], the formation of hydration products was evaluated from Ca/Si, (Al+Fe)/Ca and S/Ca ratio and the Ca/Si, (Al+Fe)/Ca and S/Ca ratio was evaluated from EDS analysis[51] and have been given in Table 7.

Table 7 shows the Ca/Si, (Al+Fe)/Ca, and S/Ca values for various mix proportions, confirming the CSH, CH, and ettringite development as shown in SEM micrographs. The lower the Ca/Si ratio, the greater the strength of the concrete. The mix proportions H2, H3, and H4 had lower Ca/Si ratios and were in the range of CSH crystal formation, resulting in increased concrete strength, as evidenced by CS findings. Due to the presence of sulphur (S) and a high Ca/Si ratio, the strength of mixes H6, H7, and H8 was reduced. Microstructural investigation utilizing SEM-EDX was used to confirm the results acquired through experimentation. The results of EDS analysis of various mix proportions followed the same pattern as the results obtained.

From the EDS analysis, it has been observed that the values of Ca/Si, (Al+Fe)/Ca, and S/Ca ratio varied from 0.841 to 4.824; 0.151 to 0.545 and 0 to 0.099 for all the mix proportions at 28 days of water curing. CSH, CH, and AFm formation in the specimens validated the experiment results. The S/Ca ratio should be low or nil for the CSH gel formation.

Table 6 — Ratio of Ca/Si, (Al+Fe)/Ca and S/Ca for hydration products[51]

Hydration product	CSH	CH	AFm
Ca/Si	0.8-2.5	≥10	≥ 4.0
(Al+Fe)/Ca	≤ 0.2	≤ 0.04	≥0.4
S/Ca	-	≤ 0.04	≥0.15

Table 7 — CS, Ca/Si, (Al+Fe)/Ca and S/Ca values for concrete specimens.

Mix No.	28 days			
	CS	Ca/Si	(Al+Fe)/Ca	S/Ca
H1	52.77	1.016	0.546	0
H2	57.12	0.841(CSH)	0.182(CSH)	0
H3	55.51	1.384(CSH)	0.246	0
H4	60.65	2.0336(CSH)	0.287	0
H5	55.24	1.263(CSH)	0.341	0
H6	46.95	1.127(CSH)	0.268	0.099
H7	42.77	1.551(CSH)	0.381	0.061
H8	45.63	4.824(AFm)	0.150(CSH)	0.003

3.8 Ecological and economic analysis

The ecological and economic analysis of concrete with additives was evaluated and compared with the plain concrete mix. The values of EE (MJ/m^3), ECO$_2$(kg CO$_2$e/m^3),and cost (INR/m^3) of concrete with different mix proportions have been given in Table 8.

Table 8 showed that adding stone waste powder to concrete reduced energy consumption, CO2 emission, and cost by 9%, 10%, and 4% respectively, whereas CN increased insignificantly compared to plain mix except for cost. CN and TEA hiked the cost by 4% and 30% as compared to plain mix. EE, ECO$_2$, and cost for unit strength were also evaluated. The inclusion of SWP and CN in concrete reduced the EE, ECO$_2$, and cost per unit strength. The addition of CN+TEA in concrete also reduced the EE and ECO$_2$ per unit strength with reference to plain mix.

At 28 days, the values of EE/unit strength, ECO$_2$/unit strength, and cost/unit strength were assessed. The addition of stone waste decreased energy usage and CO$_2$ emissions, as well as the cost of the concrete, but CN enhanced all per unit strength.

3.9 Performance evaluation

The performance evaluation of concrete of different mix proportions in terms of CS, STS, ER, EM, ecological, and economic aspects was carried out concerning plain mix at 28 days. The performance index for various concrete mixtures has been given in Table 9.

The mixes K2, K3, K4, and K5 had superior mechanical strength and ER performance at 28 days of water curing; while the rest had poor performance in plain mixes. However, in the ecological and economic aspects, mix K2 had superior performance compared to other mixes. The inclusion of SWP in concrete not only enhanced the mechanical strength but also reduced the cost, energy consumption, and

Table 8 — Ecological and economic aspects per unit strength of concrete.

Mix No.	CS	EE	ECO$_2$	Cost	EE/28D-CS	ECO$_2$/28D-CS	Cost/28 D-CS
K1	52.77	2338.74	420.94	6195	44.32	7.98	117
K2	57.12	2127.54	380.02	5975	37.25	6.65	105
K3	55.51	2338.74	420.94	6429	42.13	7.58	116
K4	60.65	2339.34	423.05	8087	38.57	6.98	133
K5	55.24	2339.34	423.05	8321	42.35	7.66	151
K6	46.95	2127.54	380.02	6209	45.31	8.09	132
K7	42.77	2128.14	382.13	7867	49.76	8.93	184
K8	45.68	2128.14	382.13	8101	46.59	8.37	177

Table 9 — Performance index of different concrete mix proportions.

Mix No.	CS	STS	ER	EM	EE	ECO_2	Cost
K1	1.00	1.00	1.00	1.00	1.00	1.00	1.00
K2	1.08	1.08	1.11	1.03	0.91	0.90	0.96
K3	1.05	1.04	1.02	1.02	1.00	1.00	1.04
K4	1.15	1.07	1.19	1.09	1.00	1.01	1.31
K5	1.05	1.06	1.10	1.00	1.00	1.01	1.34
K6	0.89	0.97	0.76	0.97	0.91	0.90	1.00
K7	0.81	0.76	0.88	0.94	0.91	0.91	1.27
K8	0.87	0.92	0.82	0.90	0.91	0.91	1.31

Table 10 — Relative error (%) of experimental and predicted value of various parameters

Mix No.	28D STS	56D STS	90D STS	180D STS	365D STS	28D ER	56D ER	90D ER	180D ER	365D ER	56D SER	90D SER	180D SER	365D SER	56D CER	90D CER	180D CER	365D CER
H1	-0.2	-1.1	1.9	3.9	3.8	0.1	-1.9	-3.8	3.7	1.5	-4.3	-1.4	-4.0	-4.4	3.6	3.0	0.5	1.4
H2	-14.4	-3.3	-6.3	-6.8	-8.0	-1.3	-3.3	-5.4	-1.6	-1.4	5.2	2.5	4.6	3.3	-10.6	-8.3	-4.9	-1.4
H3	-11.6	0.9	1.4	-0.7	3.2	3.9	3.5	2.7	0.0	-1.3	1.1	-2.7	1.3	3.7	1.5	7.5	7.6	6.7
H4	-14.5	2.1	0.7	-1.1	0.5	-1.1	-1.9	-1.8	-3.6	-0.2	-1.0	1.2	-4.2	-3.8	-6.1	-5.2	-3.7	-4.5
H5	-13.9	1.8	2.8	4.7	0.1	-4.3	1.4	4.2	1.4	0.5	0.0	-1.0	5.7	4.8	1.8	-0.7	-1.0	-0.5
H6	-11.6	-3.8	-1.3	-4.7	-42.8	14.1	10.2	11.1	-5.7	-5.1	7.8	7.2	4.2	5.0	9.6	1.6	1.1	0.6
H7	-0.3	7.8	3.6	6.0	7.4	-11.3	-9.0	-8.3	2.6	1.9	-5.7	-6.4	-4.2	-2.9	4.8	-1.2	-2.0	-1.0
H8	-9.4	-3.6	-2.1	0.4	-1.8	3.2	3.0	3.7	3.7	4.4	-1.5	1.6	-2.2	-4.3	-1.7	5.3	3.4	-0.6

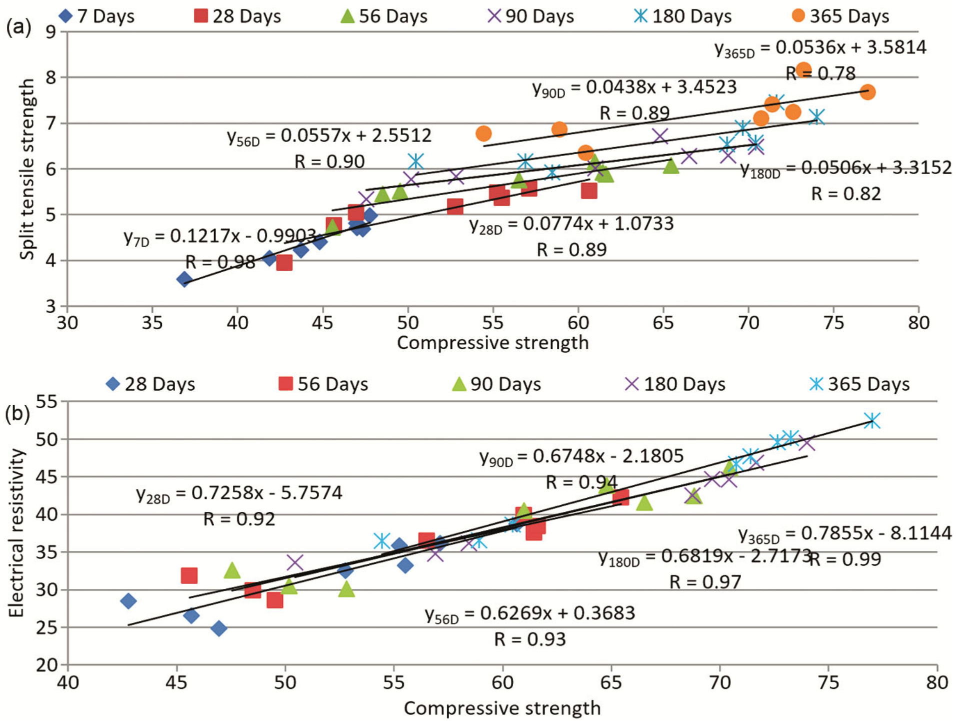

Fig. 12 — Correlation between (a) CS and STS, and (b) CS and ER under water curing.

CO_2 emission. The increase in strength and ER was higher in the case of CN in concrete than SWP, but CN enhanced the EE, ECO_2, and cost of concrete.

3.10 Correlation between various properties

The correlation between CS and STS, CS and ER underwater, sulphate, and chloride attack at various ages have been derived along with the equation. STS and ER were calculated from the equation obtained from the correlation curve. The relative error (%) was determined between experimental results and results from the derived equation; it is given in Table 10. The derived equation and Pearson linear correlation factor have been shown in Fig. 12 (a–b) for STS and ER at

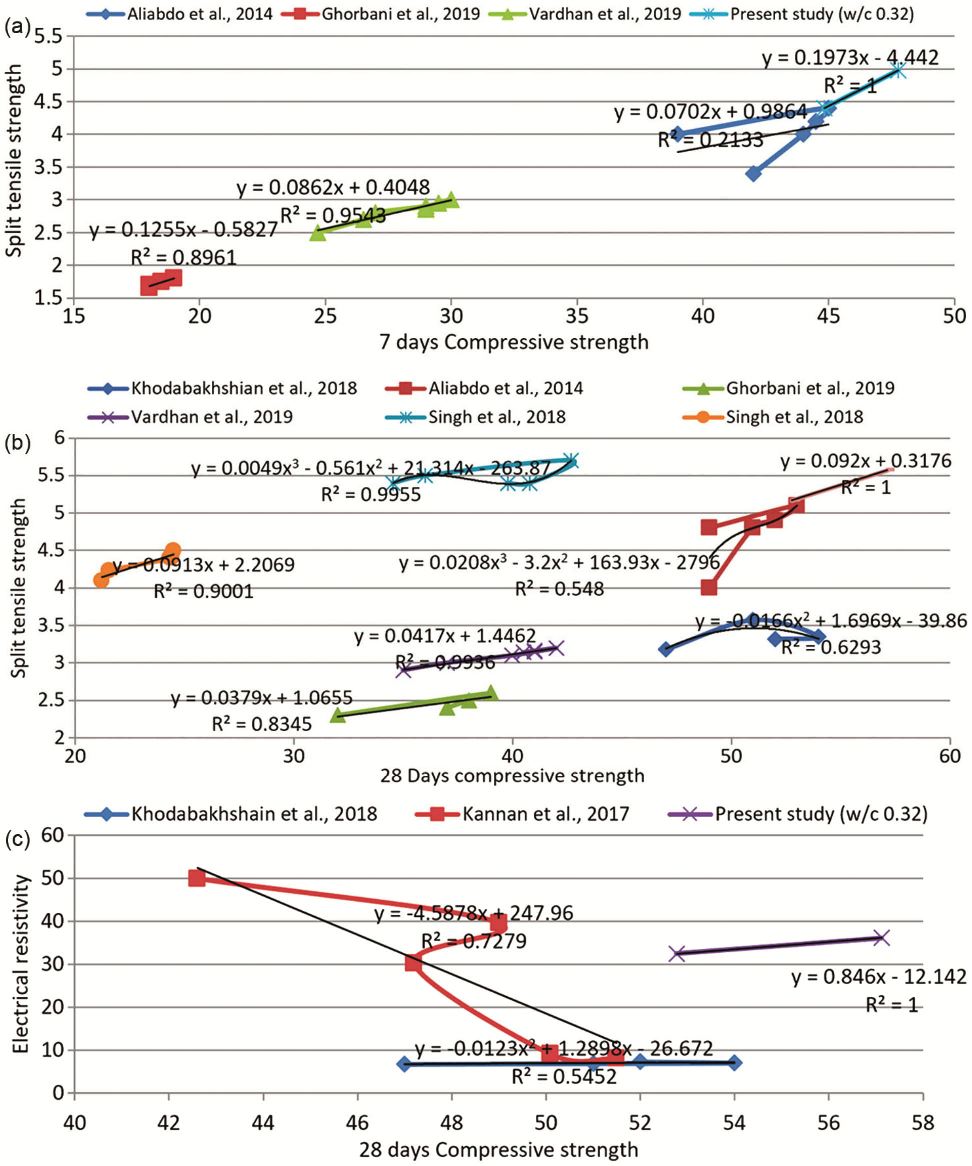

Fig. 13 — Correlation between (a) CS and STS at 7 days, (b) CS and STS at 28 days, and (c) CS and ER at 7 days of other researchers.

various ages and conditions. The relation between STS and CS was quite strong to very strong at various curing ages. The relationship between CS and ER also went from quite strong to strong in terms of water and chemical conditions. The present study's correlation between CS and STS was linear, and other researchers had linear and polynomial correlations.

For all curing conditions and ages for both concrete, the correlation between CS and STS, CS and ER were linear in this study. The connection between CS and STS at 7 and 28 days; and CS and ER at 28 days was determined from prior research and displayed in Fig. 13 (a,b& c) correspondingly. The relationship between CS and STS at 7 days was linear[39, 42-43], CS and STS at 28 days were linear[42, 43, 52] and polynomial[39, 41, 45], CS and ER at 28 days was linear[53] and polynomial[45].

4 Conclusion

Sustainable construction materials are encouraged by the consumption of natural resources and the production of greenhouse gases. Cement in concrete increases CO_2 emissions, which can be lowered by using waste as a cement substitute. The effects of CN, TEA, and SWP on workability, mechanical strength, and electrical resistivity were examined at various curing ages. The following conclusions have been observed from the above work:

- The workability of the fresh concrete decreased for all the concrete mixtures after the inclusion of accelerators and SWP due to a less plasticizing effect and higher surface area and water absorption capacity, respectively.
- Including CN, TEA, CN+TEA and SP enhanced concrete's mechanical strength and electrical resistivity. CN+SP, TEA+SP, and CN+TEA+SP had diminished performance compared to plain mix.
- A noticeable depletion in CS and ER was observed against sulphate solution attack for all mix proportions at ($28^*+28^\#$) and ($28^*+62^\#$) days except for mix K4.

The addition of CN increased electrical resistivity, but all other mix proportions decreased the electrical resistivity at the exposure to sulphate attack at $28^\#$ and $62^\#$ days. ER of different mixes decreased under sulphate solution attack than the concrete specimens at 56 and 90 days of water curing.

- High values of electrical resistivity indicate a low rate of corrosion.
- SWP reduced the energy consumption and emission of CO_2in concrete, while accelerators increased both. CN and TEA raised the cost of concrete construction, whereas stone waste decreased the cost.
- Stone waste powder had comparable results to calcium nitrate and triethanolamine in terms of strength and electrical resistivity,but, the cost of later was high. Therefore, stone waste powder was found to be an effective and efficient construction material in terms of strength and being environmentally friendly.
- The performance evaluation of concrete mixtures was also carried out in reference to plain mix. CN and SSP performed superiorly to plain mix.
- The exercise of stone waste powder in concrete may lead to cost-effective concrete that has essential properties and is environmentally friendly.

The effects of stone waste and accelerators on the performance of concrete mixtures in various aspects were studied experimentally.Accelerator and stone waste powder separately improved the performance of concrete; but, their combination had a detrimental effect on all except (CN+TEA). However, stone waste powder was found to be a cost-effective material rather than calcium nitrate and triethanolamine in terms of ecological and economic aspects. SWP produced low energy-intensive, CO2 emission, and economical end products per unit strength among all the mix proportions. Also, using stone waste powder in concrete minimizes its hazardous effects on the environment, its disposal problems, and the consumption of cement content and construction costs.

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