Influence of Pumice on the Mechanical Performance, Microstructural Characteristics, and Sustainability of Self-Compacting Earth Concrete

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ABSTRACT This study explores the potential of Pumice as a natural pozzolan in Self-Compacting Earth Concrete (SCEC), focusing on its effects on physical, mechanical, microstructural properties, and Life Cycle Analysis (LCA). According to earth concrete design mixtures, clay is substituted for cement in amounts of 50%, 60%, 70%, and 80%. Also, SCEC-C50 mixture were prepared with varying Pumice contents (10%, 15%, 25%, 35%) to assess their properties. A 15% Pumice mixture exhibited compressive strength similar to that of SCEC with 50% earth after long-term curing. Additionally, Pumice improved ultrasonic pulse velocity (UPV) and microstructure, promoting CH and C-S-H production while minimizing ettringite formation. Incorporating Pumice at 15% reduced environmental impact, decreasing CO_2 emissions and environmental weight by approximately 53%. This research highlights pumice-based SCEC as a promising eco-friendly alternative in the construction industry.

Keywords: CO_2 emission, Self-Compacted Earth Concrete (SCEC), Pumice, Superplasticizer, Life Cycle Assessment (LCA).

I. INTRODUCTION

Global warming is a critical challenge, and addressing its impacts requires collective efforts across sectors, with the construction industry playing a key role due to its significant resource consumption and CO_2 emissions. Cement production alone contributes to 8% of global carbon emissions, emphasizing the need for sustainable alternatives (Nevitt, 2023; Shirvani et al., 2023). Earth-based construction methods, such as Self-Compacting Earth Concrete (SCEC), which combine the benefits of Self-Compacting Concrete (SCC) and Earth Concrete (EC), offer a potential solution by reducing CO_2 emissions and energy consumption (Kohandelnia, 2023). However, the use of earth concrete in construction is hindered by issues such as low compressive strength, limiting its adoption in load-bearing applications. While there is limited research on earth concrete, studies suggest that incorporating stabilizers like GGBS, fly ash, and fibers can improve its strength and performance (LAM et al., 2023; Mohsen et al., 2023). Pumice, a natural pozzolan, has been shown to enhance the properties of cement-based materials by improving their mechanical strength and durability, while also reducing environmental impacts. Previous studies on pumice-based concrete have indicated improvements in compressive strength and reductions in CO_2 emissions when used as a cement substitute (Samimi et al., 2022). However, its impact on earth concrete has not been sufficiently explored, highlighting a gap in the literature. This study aims to address this gap by developing an eco-friendly SCEC with varying proportions of earth and pumice as cement replacements. The research focuses on optimizing the mix design to reduce CO_2 emissions while ensuring the required mechanical strength for both structural and non-structural elements. The study evaluates the mechanical performance, and microstructural characteristics of the SCEC mixtures, along with conducting a Life Cycle Assessment (LCA) to compare the environmental impacts and costs. In fact, the aim is to establish pumice-based SCEC as a sustainable alternative to traditional concrete in the construction industry, aligning with global sustainability objectives.

In this study, first, to assess the mechanical behavior of the SCEC mixtures, a range of mechanical properties were tested. Then, the UPV test is measured for all concrete mixtures studied. Next, microstructural analyses were performed on the different mixtures using field emission scanning electron microscopy (FESEM). Finally, life cycle assessment (LCA) results evaluating impacts on ecosystems, CO_2 emissions, human health, natural resources, and overall costs were compared across the different mixtures.

II. Material and Experimental program

In this study, the earth from Qaemshahr, located in northern Iran, was used for the production of concrete. X-ray Diffraction (XRD) analysis revealed that the earth contained quartz, calcite, muscovite, and goethite, with variations in the intensity of mineral composition (Khodaparast et al., 2024). The specific gravity of the selected earth sample was 2.75. Portland cement type II from tehran and pumice from Khash were used .Crushed angular aggregates (0–4 mm and 6–12 mm) were used, along with a Polycarboxylate ether superplasticizer to reduce water demand.

Mix design of concrete

The study focused on designing concrete mixtures to evaluate the impact of earth and pumice substitution on Self-Compacting Earth Concrete (SCEC). According to Table 1, the concrete mixtures were divided into two groups : Group 1 included four mixtures with earth substitution levels ranging from 50% to 80%, labeled SCEC-C50, SCEC-C60, SCEC-C70, and SCEC-C80. Group 2 focused on the SCEC-C50 mixture, which was mixed with pumice as a cement replacement at 10%, 15%, 25%, and 35%, resulting in mixtures SCEC-C50-P10, SCEC-C50-P15, SCEC-C50-P25, and SCEC-C50-P35. The water/binder ratio was kept constant at 0.4, and a superplasticizer was used to achieve a standard slump flow.

Table 1. **Mix proportions of concrete mixtures (kg/m³)**

Mix ID	Gravel (Kg/m³)	Sand (Kg/m³)	Cement (Kg/m³)	Earth (Kg/m³)	Pumice (Kg/m³)	Water (Kg/m³)	SP (Kg/m³)	W/b
reference	790	790	450	0	0	180	4.11	0.4
SCEC-C50	790	790	225	225	0	180	9.77	0.4
SCEC-C60	790	790	180	270	0	180	10.02	0.4
SCEC-C70	790	790	135	315	0	180	14.05	0.4
SCEC-C80	790	790	90	360	0	180	15.83	0.4
SCEC-C50-P10	790	790	202.50	225	22.50	180	9.17	0.4
SCEC-C50-P15	790	790	191.25	225	33.75	180	8.67	0.4
SCEC-C50-P25	790	790	168.75	225	56.25	180	8.33	0.4
SCEC-C50-P35	790	790	146.25	225	78.75	180	8.23	0.4

Casting, curing, and mixing process for concrete

The concrete samples were cast following ASTM C511 standards (ASTM C511-03, 2003). After 24 hours, the cubic and cylindrical samples were demolded and cured at a controlled room temperature with 50 ± 1% humidity, avoiding direct contact with water until the testing age. For the mixing process, fine and coarse aggregates were added to the mixer and mixed for three minutes, with 1/3 of the required water included. After adding the powder materials, the mixture was mixed for an additional minute, followed by the remaining water and superplasticizer, and mixing continued for two more minutes at a constant speed of 140 rpm.

Compressive strength test

The compressive strength of each concrete mixtures was tested on cubes (100×100×100 mm³) at 3, 7, 28, 56, 90, and 180 days of aging. Three samples were tested for each mixture, and the average value was calculated. The loading rate was 0.22 MPa/s, following ASTM C39/C39M-18 standards (C39-01 and ASTM C39-01, 2003).

Ultrasonic pulse velocity (UPV) test

The UPV test, performed on 100×100×100 mm³ cube specimens according to ASTM C597, measures the compression pulse velocity to assess the strength and quality of concrete. Higher velocities indicate better uniformity and quality, while lower velocities may suggest the presence of cracks or voids. Three measurements were taken for each specimen (ASTM C597, 2016).

SEM-EDX analysis

A Philips Xpert scattering system was used to analyze powders of three earth types and various paste mixtures. The analysis was conducted with Cu K radiation (λ = 1.5406) at 40 kV and 30 mA, scanning from 5° to 80° (2θ) with a step size of 0.02° (2θ) and a scan speed of 2 seconds per step. FESEM was used to analyze the morphology of samples after gold deposition, utilizing a Quanta 200 from FEI. The electron microscopy findings, along with elemental microanalysis, were evaluated using X-ray spectroscopy on SCEC specimens.

Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) of the reference and all SCEC mixtures was conducted using SimaPro. The overall cost of the mixtures was calculated based on local vendor reports, with the functional unit being one cubic meter of concrete (PRé and Authors, 2020). The cost of materials in all mixtures was obtained from local vendor reports. According to Dabaghi et al. (Dabbaghi et al., 2021), Equation (1) represents a normalized cost relationship based on the cement variable :

$$COSTi\ = (1 \times Ci) + (0.02 \times Ei) + (0.045 \times Pi) + (0.0025 \times Wi) + (0.225 \times Sai) + (0.22 \times Gri) + (50 \times SPi) \qquad \text{(eq. 1)}$$

Where COSTi is the normalized cost per m^3 for the ith mixture, and Ci, Ei, Pi, Wi, Sai, Gri, and SPi represent the quantities (kg/m^3) of cement, earth, pumice, water, sand, gravel, and superplasticizer in the ith mixture, respectively.

III. Results and discussion

Compressive strength

The compressive strength results for various concrete mixtures over 3, 7, 28, 56, 90, and 180 days show that the SCEC-C80 mixture had the lowest strength at all ages, while the reference mixture had the highest (See Figure. 1). The SCEC-C50 mixture exhibited a significant reduction in strength compared to the reference, with a decrease of up to 65.38% at 3 days and 51.24% at 180 days. As the earth replacement percentage increased, the compressive strength decreased, particularly in the SCEC-C80 mixture, which showed a 69.78% reduction in strength at 3 days compared to SCEC-C50. Incorporating earth as a cement replacement generally did not improve compressive strength. For the pumice-based mixtures, the compressive strength decreased by 11% to 39% at 28 days compared to the SCEC-C50 mixture. However, at 90 and 180 days, the strength of the SCEC-C50-P15 mixture reached comparable values to the SCEC-C50 mixture (Samimi et al., 2022). The strength reduction in SCEC mixtures is attributed to the decrease in cement clinker content due to earth substitution. Pumice's weak pozzolanic activity during the early stages contributed to the lower strength, but its effective pozzolanic reaction over time improved strength, consistent with findings from other studies (Khodaparast et al., 2024).

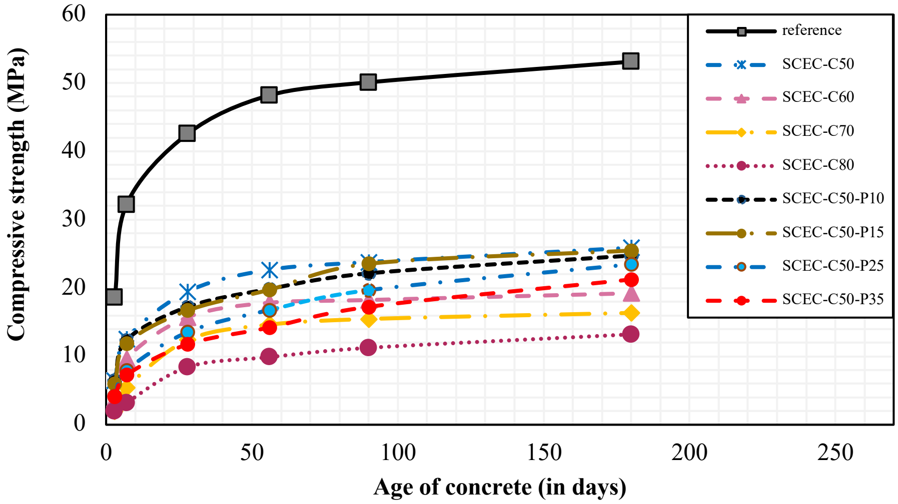
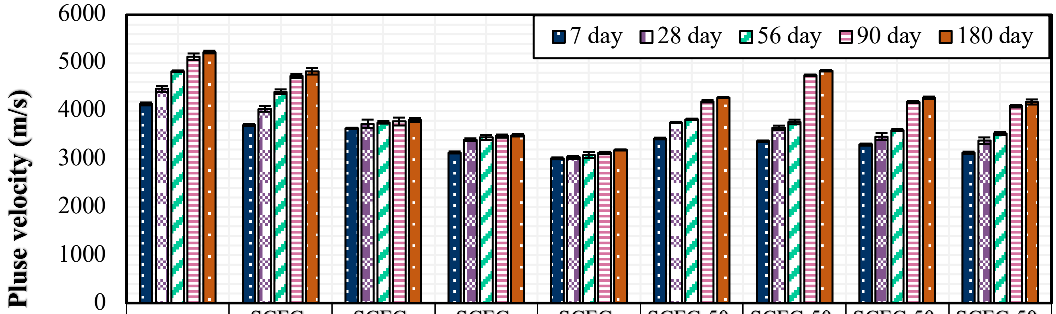


FIGURE 1. The compressive strength of studied mixtures at 3, 7, 28, 56, 90 and 180 days.

Ultrasonic pulse velocity (UPV)

As shown in Figure.2, Ultrasonic Pulse Velocity (UPV) testing showed that the reference mixture had the highest UPV value (5225 m/s), while the SCEC-C80 mixture had the lowest (3012.05 m/s). Higher earth content led to reduced UPV, indicating increased porosity and lower density, which correlated with lower compressive strength. The UPV values showed a strong correlation with compressive strength ($R^2= 0.9$), making UPV an effective porosity indicator. Pumice-based mixtures, like SCEC-C50-P15, showed improved UPV over time despite early reductions, suggesting long-term benefits of pumice in earth concrete (Samimi et al., 2022).



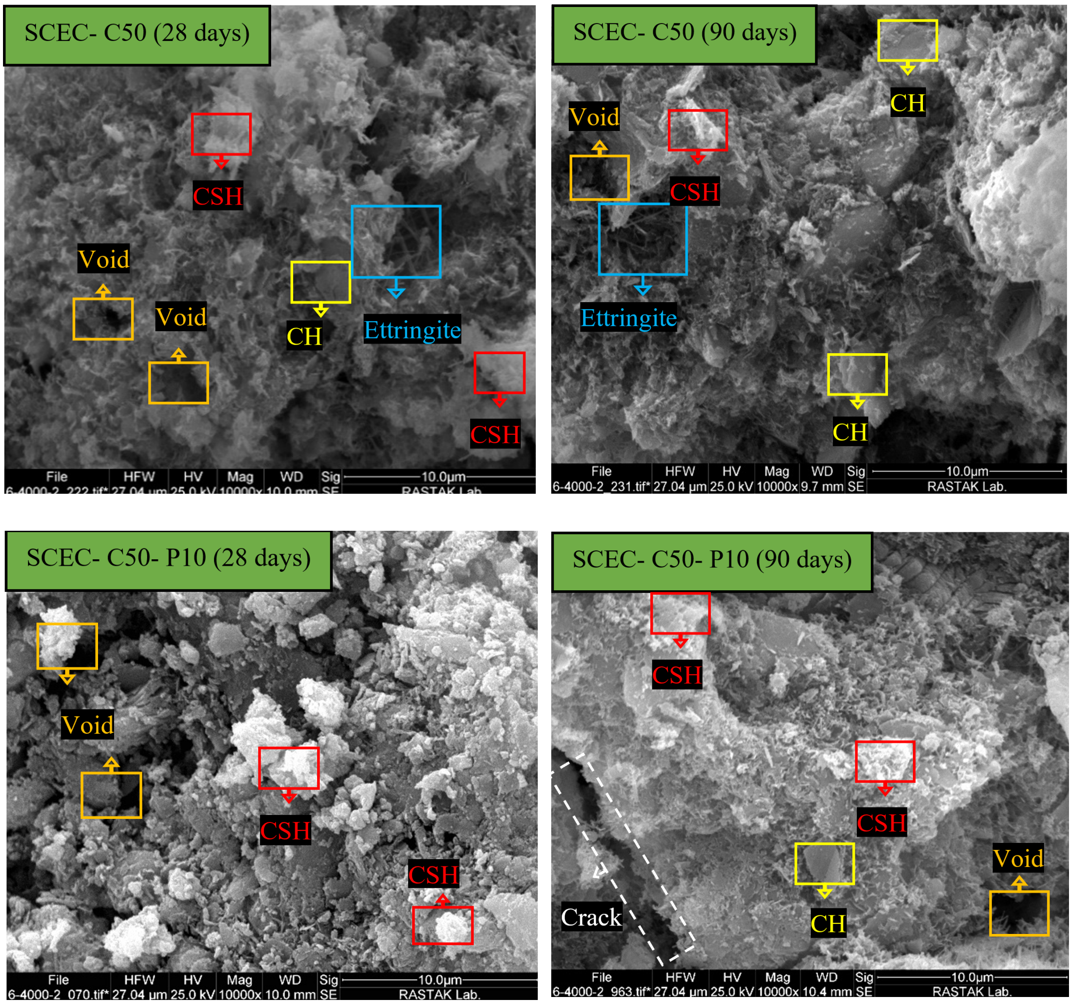
	refrence	SCEC-C50	SCEC-C60	SCEC-C70	SCEC-C80	SCEC-50-P10	SCEC-50-P15	SCEC-50-P25	SCEC-50-P35
■7 day	4145,00	3703,70	3636,36	3134,80	3012,05	3425,36	3369,58	3298,45	3125,36
▨28 day	4456,00	4042,00	3731,42	3401,36	3030,30	3758,45	3647,98	3469,41	3378,96
□56 day	4824,00	4398,00	3761,00	3446,00	3078,00	3825,36	3769,35	3598,36	3532,36
▤90 day	5125,85	4723,00	3778,51	3475,15	3126,32	4198,69	4739,00	4185,69	4099,12
■180 day	5225,00	4825,00	3810,00	3495,00	3187,00	4278,12	4835,00	4274,36	4185,34

Mix ID

FIGURE 2. UPV values of all studied mixtures at different ages.

Scanning electron microscopy (SEM)

The SEM images revealed that the reference mixture had a denser structure compared to SCEC mixtures, with increasing earth content leading to unfilled CSH fabric, uncrossed ettringite crystals, and more microcracks and voids. Based on Figure. 3, Pumice-containing mixtures showed improvement in hydration products over time, particularly in SCEC-C50-P35, which exhibited significant morphological changes after 90 days. EDX analysis showed that increasing earth substitution reduced the Ca/Si ratio, with pumice-containing mixtures also following a similar trend. Long-term curing enhanced the microstructure, reducing microcracks and voids, especially in pumice-based mixtures, due to the formation of ettringite and the high surface area of pumice promoting hydration. This indicates that pumice improves the durability and strength of SCEC mixtures by enhancing pozzolanic reactions and refining the microstructure. These findings align with the mechanical strength results, confirming pumice's beneficial role in eco-friendly and resilient SCEC formulations.



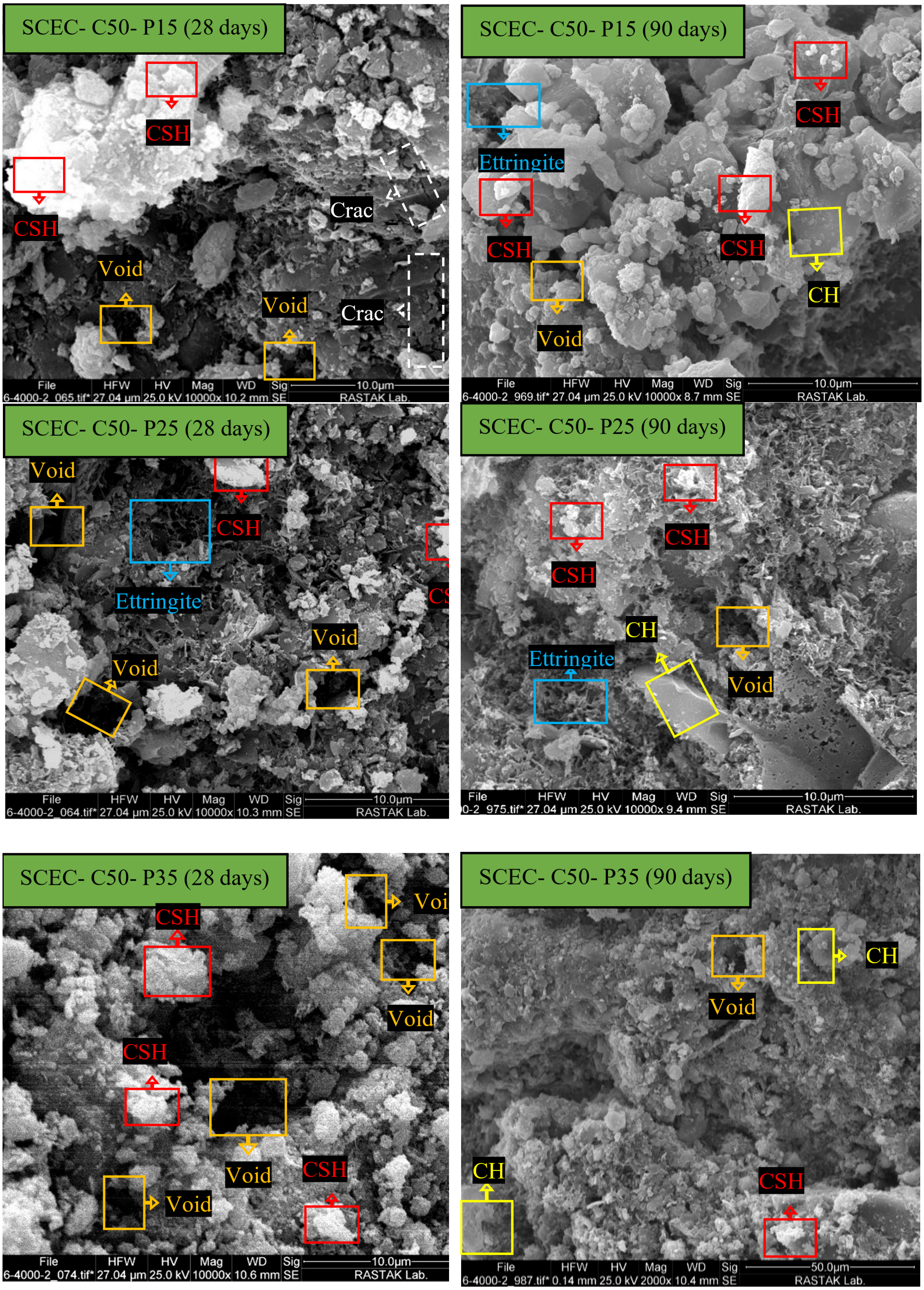


FIGURE 3. SEM of SCEC-C50 and pumice-containing mixtures at 28 and 90 days of curing age.

LCA

The environmental impact of the mixtures, as shown in Table 2, indicates that the reference mixture has the highest impact in all categories, with a total weighting of 43.05 points. In contrast, the SCEC-C80 mixture had the lowest environmental impact. Substituting earth for cement significantly reduced the total environmental impact, with reductions of 41.13%, 50.01%, 56.07%, and 63.81% for 50%, 60%, 70%, and 80% earth substitutions, respectively. Additionally, replacing cement with pumice reduced the total environmental impact of the SCEC-C50 mixture by up to 28.76%. These results suggest that using earth and pumice as replacements for cement can substantially lower the environmental impact of concrete. Table 3 aslo shows the concrete cost per cubic meter for each mixture. The SCEC-C50-P35 mixture had the lowest normalized cost, while SCEC-C80 had the highest. Pumice substitution significantly reduced the amount of superplasticizer required, leading to lower costs for SCEC mixtures. As pumice content increased, the normalized costs decreased by 4.81%, 8.15%, 11.74%, and 14.22% compared to the SCEC-C50 mixture.

Table 2. **LCA stage results.**

Mixture ID	**Human health (Daly)**	**Ecosystems (Species.yr)**	**Resources (USD 2013)**	**Total weighting (Point)**
reference	8.34	11.71	14.43	43.05
SCEC-C50	4.94	6.59	10.7	25.34
SCEC-C60	4.21	5.52	9.75	21.51
SCEC-C70	3.71	4.65	9.69	18.91
SCEC-C80	3.07	3.66	9.11	15.57
SCEC-C50-P10	4.52	6.02	10.07	23.21
SCEC-C50-P15	4.31	5.72	9.71	22.07
SCEC-C50-P25	3.91	5.16	9.13	20.02
SCEC-C50-P35	3.52	4.62	8.62	18.04

Table 3. Concrete mix proportions cost per m3.

Mixture ID	**Gravel**	**Sand**	**Cement**	**Earth**	**Pumice**	**Water**	**SP**	**Normalized cost**
reference	173.8	177.75	450	0	0	0.45	205.5	1007.5
SCEC-C50	173.8	177.75	225	4.5	0	0.45	488.5	1070
SCEC-C60	173.8	177.75	180	5.4	0	0.45	501	1038.4
SCEC-C70	173.8	177.75	135	6.3	0	0.45	702.5	1195.8
SCEC-C80	173.8	177.75	90	7.2	0	0.45	791.5	1240.7
SCEC-C50-P10	173.8	177.75	202.5	4.5	1.01	0.45	458.5	1018.51
SCEC-C50-P15	173.8	177.75	191.25	4.5	1.52	0.45	433.5	982.76
SCEC-C50-P25	173.8	177.75	168.75	4.5	2.53	0.45	416.5	944.28
SCEC-C50-P35	173.8	177.75	146.25	4.5	3.54	0.45	411.5	917.79

IV. Conclusion

This study explored the use of self-compacting earth concrete to reduce cement consumption by incorporating pumice content. The key findings are as follows:

1. The compressive strength of SCEC mixtures is lower than that of the reference mixture at all curing ages due to reduced clinker content and the hydrophilic properties of earth, which consume water needed for cement hydration. Specifically, the SCEC-C50 mixture shows a 65% to 51% reduction in compressive strength at 3 to 180 days compared to the reference mixture. However, the SCEC-C50-P15 mixture, despite having less clinker, exhibits comparable long-term strength due to the pozzolanic reaction of pumice, which produces CH and secondary CSH gel, resulting in compressive strengths of 23.55 MPa and 25.48 MPa at 90 and 180 days, respectively.
2. The UPV of the SCEC mixtures decreases with the substitution of earth for cement at all curing ages because of empty space and lack of homogeneity created by the inadequate hydration process. Furthermore, substituting pumice for cement decreases the UPV in the SCEC mixtures at an early curing age. However, the SCEC-C50-P15 mixture, due to the long-term pozzolanic effects of pumice, has comparable UPV results to that of the SCEC-C50 mixture.
3. SEM imaging demonstrated significantly higher CSH formation in pumice-containing SCEC mixtures at 90 days compared to early ages, further confirming the beneficial long-term effects of pumice incorporation.
4. The LCA analysis shows that substituting earth and pumice for cement decreased the total weighting parameter and CO_2 emissions of SCEC mixtures compared to the reference mixture due to the low clinker content. In addition, the total environmental weight and CO_2 emissions of the SCEC-C50-P15 mixture decreased by 48.73% and 52.93% compared to the reference mixture, respectively.
5. The cost estimation analysis shows that substituting pumice with cement, due to the decreased utilized SP content, plays a major role in decreasing the ultimate normalized cost of the SCEC mixtures. From the results, replacing 10%, 15%, 25%, and 35% pumice with cement decreased the normalized costs by 4.81%, 8.15%, 11.74%, and 14.22%, compared to the SCEC-C50 mixture, respectively.

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