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Use of slag and hemp for enhancing the strength and durability properties of concrete - A case study

Uso de escoria y cáñamo para mejorar las propiedades de resistencia y durabilidad del hormigón: un estudio de caso

Rameshkumar, Vighnesh * [1]; Devi S., Vaishnavi **

* Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore, Tamilnadu, India.
** Department of Civil Engineering, Thiagarajar College of Engineering, Madurai, Tamilnadu, India.

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Abstract

Concrete is one of the most important components utilized in the building sector. The shrinkage of the concrete throughout the curing process could end up in microcracks. These cracks function as channels for fluids to infiltrate the concrete. Under optimal circumstances, the fluids within the concrete undergo various reactions that lower the pH of the concrete core, leaving the reinforcing bars susceptible to corrosion. The solution to these problems could be combining slag and hemp into concrete. Four mixes, namely conventional concrete (CC), hempcrete (M1), slag-integrated concrete (M2), and slag-integrated hempcrete (M3), were used to study mechanical properties, durability properties, and microstructure. The slag was substituted for the fine aggregates by 50%, and hemp was taken as 3% of the binder for the mixes. The study showed that the slag-integrated hempcrete was superior in strength and durability properties compared to the other mixes. Slag filled the pores in the hemp and aggregates, making them denser and stronger overall. The reduction in porosity enhanced the durability attributes even further. Moreover, the hemp improved the binding quality, which improved strength and friction. The FESEM images provided visual confirmation of the reduced permeability of the mix. The integration of slag and hemp into concrete results in a sustainable mix and could be a solution to the extraction of resources.

Keywords: Strength and durability properties, Slag, Hempcrete, Microstructure, sustainable practices.

Resumen

El hormigón es uno de los componentes más importantes de la construcción. La retracción del hormigón durante el curado puede provocar microfisuras. Estas fisuras actúan como canales de infiltración de fluidos. En condiciones óptimas, los fluidos del hormigón experimentan diversas reacciones que reducen el pH del núcleo, dejando las barras de refuerzo susceptibles a la corrosión. La solución a estos problemas podría ser la combinación de escoria y cáñamo en el hormigón. Se utilizaron cuatro mezclas: hormigón convencional (CC), hormigón de cáñamo (M1), hormigón con escoria integrada (M2) y hormigón de cáñamo con escoria integrada (M3) para estudiar las propiedades mecánicas, la durabilidad y la microestructura. La escoria sustituyó los áridos finos en un 50% y el cáñamo se utilizó en una proporción del 3% del aglutinante para las mezclas. El estudio demostró que el hormigón de cáñamo con escoria integrada presentaba una resistencia y durabilidad superiores a las demás mezclas. La escoria rellenó los poros del cáñamo y los áridos, haciéndolos más densos y resistentes en general. La reducción de la porosidad mejoró aún más la durabilidad. Además, el cáñamo mejoró la calidad de la adherencia, lo que mejoró la resistencia y la fricción. Las imágenes FESEM confirmaron visualmente la menor permeabilidad de la mezcla. La integración de escoria y cáñamo en el hormigón da como resultado una mezcla sostenible y podría ser una solución a la extracción de recursos.

Keywords: Propiedades de resistencia y durabilidad; Escoria; Hormigón de cáñamo; Microestructura; Prácticas sostenibles.

Corresponding author: vighneshr@skcet.ac.in
Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore, Tamilnadu, India

1. Introduction

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Copper slag, or slag, is a residual material generated during copper production. A recent study showed that around 25 million tons of copper slag was generated as a by-product on a global scale from copper smelting (Thomas and Bremner, 2012). It is further projected that for each ton of copper produced, there is an average generation of 5 tons of slag generated as a by-product (Wang et al., 2023). Several investigations have been conducted to investigate the long-term durability of slag in seawater (Rashad et al., 2023). The researchers conducted experiments on the engineering features of a copper slag, fly ash, and polymer mixture (Edwin et al., 2017). The primary aim of the studies was to assess the impact of materials like fly ash, dolime concentration, and curing time on copper slag strength and stiffness properties. Numerous research investigations have been conducted to investigate the leachability of copper slag (Madheswaran et al., 2014); (Mithun and Narasimhan, 2016); (Singh et al., 2022). The leaching investigations of copper slag were conducted using three different aqueous media: tap water, rainwater, and seawater. The pH values for drinking water, rainwater, and saltwater are 7.00, 2.92, and 8.98, respectively. The slag specimens were immersed in purified water and subsequently analyzed for leaching over 15 days using the inductively coupled plasma (ICP) method. There was no evidence of leaching of contaminants, including Pb, Zn, Cr, Ni, Mo, and others. On the 15th day, there was the release of tiny amounts of barium (0.01 parts per million), copper (0.09 parts per million), manganese (0.09 parts per million), and strontium (0.002 parts per million). The findings from the leachate investigations indicated that the presence of slag inside concrete does not facilitate the leaching of detrimental elements, such as Cu and Fe, that are present in the slag. Therefore, it did not provide any environmental concerns. The present-day application of copper slag is limited to around 20% of the total quantity produced (Sasanipour and Aslani, 2020). The residual materials were used in low-value-added applications. The disposal of this material mandates extensive land usage, which would result in unsustainable practices. A study by Perez et al., (2021) showed that the addition of Bottom slag and fly ash enhanced the ductile behavior of the specimen under axial force. In addition, the specimen showed better fresh and hardened concrete properties. Sakthieswaran, (2023) studied the effect of adding copper furnace slag, and metakaolin for improving the performance of concrete. The authors used 40% slag and 5% metakaolin to enhance the strength and durability properties, which was validated by microstructure analysis.

Hemp, formally referred to as Cannabis sativa, has seen a significant surge in its use across several sectors, such as medicine, food production, apparel, and the construction field (Ahmed et al., 2022). Furthermore, it was worth noting that industrial hemp plants can sequester a net carbon amount of 0.7 tons/year through their method of trapping carbon dioxide during their growth phase. The rapid growth rates of this particular crop also contribute to its exceptional capacity for converting CO_2 into biomass (Abdellatef and Kavgic, 2020). In view of the growing attention towards incorporating natural fibers in the construction field, hemp has emerged as a promising material due to its distinct characteristics. Specifically, hemp has been gaining traction in the building industry due to its lightweight nature, low density, low thermal conductivity, and exceptional acoustic insulation properties (Ip and Miller, 2012). The initial application of hemp in construction can be traced back to the 1990s when it was utilized as a bio-based concrete known as "hempcrete." (Jami et al., 2019). This material consisted of a mixture of hemp shives or hurds, a lime-based binder, water, and sand. In recent years, hempcrete has been used to construct the first skyscraper (Shang and Tariku, 2021). However, it has been observed that hemp-based composite products exhibit lower mechanical strength compared to traditional concrete materials. Consequently, hempcrete was generally utilized solely for non-structural purposes. According to another study, using hemp as a substitute for aggregate has been found to decrease the mechanical strength of the composite material (Chen et al., 2019). Existing research on hemp concrete has mostly concentrated on the environmentally friendly aspects of its utilization, such as decreased CO_2 emissions, moisture buffering capabilities, and its effectiveness as a thermal and acoustic insulator (Jorge et al., 2004). In the past few years, there has been a notable increase in the utilization of lime-hemp concrete worldwide. Hemp concrete is a composite material that consists of hemp shiv and cement. The binder can be supplemented with pozzolans and cements to expedite curing (Nazmul et al., 2023). Another study shows that hempcrete was a carbon dioxide (CO_2) sink, sequestering more than 100 kilograms of CO_2 per cubic meter of hempcrete wall (Tam et al., 2018). The research indicated a correlation between lignocellulosic materials and Ca2+ found in mineral binders. Another study done by Sedan et al., (2007) demonstrated the presence of a comparable process in hempcrete composites, wherein pectin molecules effectively trap Ca2+ ions to generate stable chelate complexes. Furthermore, previous studies have documented the presence of comparable interaction processes in hemp-cement composites. A recent study by Balčiūnas et al., (2018) examined the constitution and microstructure of hempcrete composites. The absence of portlandite and the identification of unaltered minerals were documented by the researchers following the curing period. These findings confirm the hindrance of cement's early-stage hydration caused by including hemp particles.

The extensive literature review showed that the inclusion of either hemp or slag into the concrete increased the overall strength and durability of the specimen. However, to the best knowledge of the authors, the research on the integration of both hemp and slag was not utilized for improving the overall performance of concrete. In this paper, the authors integrated hemp and slag into concrete to compare its performance with conventional concrete. The mechanical and durability properties of the four configurations, namely, hempcrete (M1), slag-integrated

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concrete (M2), slag-integrated hempcrete (M3), and conventional concrete (CC), were used in the study. The strength and durability results were validated using microstructure analysis through FESEM.

2. Materials

2.1 Concrete, Copper Slag and Hemp

Pozzolana Portland Cement (PPC) was utilized as the binding agent in concrete conforming to IS: 1489 (IS 1489-(1): 1991 Portland-Pozzolana Cement Specification PART-1 Fly-Ash Based,). The study utilized locally sourced fine and coarse aggregates that conform to the specifications stated in IS: 383(IS 383: 1970 Specification for Coarse and Fine Aggregates from Natural Sources for Concrete, n.d.). Copper slag is the residual substance generated during the copper production process and was utilized in the study. The particle size distribution was done on the slag sample, and it was found that the sizes were similar to the dimensions of fine aggregates. The fine aggregates were replaced by the slag by 50% of the weight in this study (Schlesinger et al., 2022); (Sukmawan et al., 2016). The hemp shives (3% of binder) utilized in the cases were cultivated and sourced from Coimbatore, Tamilnadu, India. (Figure 1) illustrates the particle size distribution of the hemp sample. The hemp particles were washed under running water to eliminate dust particles. Subsequently, the shives were subjected to oven drying for 24 hours before commencing the experimental study. The reduction in the weight of the hemp particles was attributed to the washing and drying method, which effectively eliminated a considerable quantity of dust (Bhoi et al., 2018). The properties of hemp and slag are tabulated in (Table 1) and (Table 2), respectively. The chemical properties provided in (Table 2) were obtained using XRD and were provided by the seller of the materials. (Figure 2) shows the hemp and slag samples taken for the study.

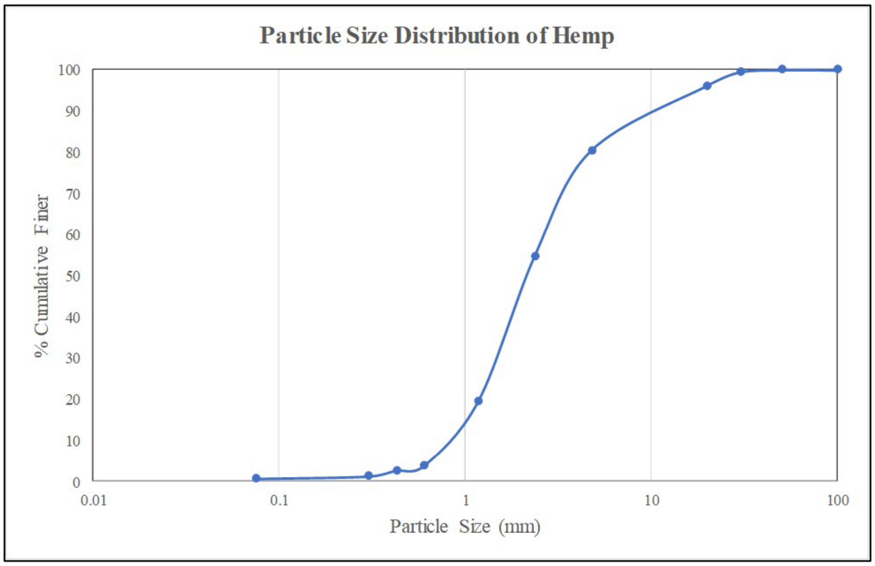

Figure 1. PSD curve for Slag sample.

Table 1. Properties of hemp Shive.

Size of hemp (mm)	2.36 to 4.75
Bulk Density (kg/m^3)	101.25
Water absorption after 48 h using washed samples (%)	258
Water absorption after 48 h using unwashed samples (%)	156
Desorption (%)	96.21

Table 2. Properties of Copper slag and cement.

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Chemical Properties done through XRD.		
Constituent	Copper Slag	Cement
CaO	8.1	65
SiO_2	24.9	23
Al_2O_3	5.2	5.68
Fe_2O_3	45.2	3.4
MgO	0.8	1.4
Na_2O	0.8	1.5
K_2O	0.3	1.6
SO_3	0.3	NA
P_2O_5	0.7	
TiO_2	0.2	
ZnO	7.2	
MnO	0.9	
Cr_2O_3	1	
PbO	0.5	
Physical Properties		
Minimum Size	1.28 mm	16 µm
Specific gravity	3.62 g/cm^3	3.15 g/cm^3

Figure 2. Hemp and slag used for the study.

2.2 Sample Preparation

The sample preparation was conducted in accordance with the requirements specified by IS 10262:2009 for the M25 mix proportion (IS10262, 2009) Recommended Guidelines for Concrete Mix Design. Bureau of Indian Standards., n.d.). The composition of the mixture included cement, coarse aggregate measuring 16 mm, and fine aggregate including M-sand, slag, and hemp shives. A water-to-cement ratio of 0.45 was used to enhance the workability of the material. The mixing method utilized potable water that adhered to the standards outlined in IS 456:2000 (IS 456, 2000), Plain and Reinforced Concrete – Code of Practice. Bureau of Indian Standards., n.d.). The components were combined in a pan mixer. The compaction of the mixtures was achieved by the utilization of traditional tamping rods. The specimens were removed from the molds after 24 hours. The specimens were immersed in water for curing purposes and later subjected to testing under saturated surface dry conditions at the specified age. The mix ratios employed for the experimental trials have been tabulated in (Table 3).

Table 3. Mix Proportions used for the study.

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Description	Cement (kg/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	Water (lit/m³)	Copper slag (kg/m³)	Hemp Shive (kg/m³)
CC	438.13	688.14	1069.47	197.23	-	-
M1	424.98	688.14	1069.47	197.23	-	13.1431
M2	438.13	344.07	1069.47	197.23	344.07	-
M3	424.98	344.07	1069.47	197.23	344.07	13.143
M1 – Concrete + Hemp (3% of binder), M2 - Concrete + Slag (50% of FA) and M3 – Concrete + slag (50% of FA) + Hemp (3% of binder)						

3. Test Methods

3.1 Testing of Specimens in terms of strength

he test for compressive strength was done using six specimens measuring 150 x 150 x 150 mm for each mix. Subsequently, three specimens from each mix were subjected to testing after a curing period of 7 and 28 days. Similarly, the flexure testing was conducted using six prism specimens of 500 x 100 x 100 mm for each mix. Subsequently, three specimens were subjected to flexure testing after a curing period of 7 and 28 days. The cube compressive strength and flexure strength tests were done in accordance with the IS: 516:1959 (IS: 516, 1959, Methods of Tests for Strength of Concrete. Amendment No. 2, Reprint 1993. Bureau of Indian Standards., n.d.). The strength tests were performed with compression testing equipment with a capacity of 1,000 kN and flexure testing equipment with a capacity of 100 kN.

3.2 Testing of Specimens in terms of durability

The water absorption test was conducted for all mixes with a cube specimen of size 150 mm. First, the specimens (3 numbers per mix) were oven-dried at a controlled temperature for one day. Subsequently, the specimens were fully submerged in water for 2 days. The water absorption values were determined following the ASTM standards (ASTM C 642-06. Standard Test for Density, Absorption and Voids in Hardened Concrete., .). The resistance of concrete to acid penetration was conducted using a 5% sulfuric acid solution in which the specimens were immersed for 4 weeks after 28 days of water curing. The cube specimens of 150 mm (9 per mix) were taken and immersed into the acid solution. The solution was changed weekly to maintain the same acidic environment and the specimens were tested for compression strength after 7,14 and 28 days of immersion using (Equation 1) (Rameshkumar et al., 2022).

$$Decrease\ in\ compression\ strength = \frac{Strength\ before\ immersion - Strength\ after\ immersion}{Strength\ before\ immersion} * 100 \tag{1}$$

3.3 Testing of Specimen in terms of microstructure

The microstructure of the specimen was examined using a Field Emission Scanning Electron Microscope (FESEM). For the FESEM study, tiny pieces were extracted following the strength tests and oven-dried. The Dust was removed from the specimens and sputter-coated using a Turbo-Pumped Sputter Coater. The coating ensured that clear images were produced from the microscope test.

4. Discussions

4.1 Testing of specimen – Compression strength

The compression strength was done for all mixes after 7 and 28 days of curing as shown in (Figure 3) (with 5% error bars). Conventional Concrete (CC) produced 7th and 28th strengths of 16.23 MPa and 25.36 MPa, respectively, which was the least strength of all mixes. The hempcrete (M1) produced strengths of 19.67 MPa and 29.36 MPa after the same periods of curing. The hemp fiber specimens resulted in higher strengths since the fibers resisted the loads using higher friction. The slag-integrated concrete (M2) showed 17.63 MPa and 26.87 MPa for the 7th and 28th-day strength, respectively. The slag tends to occupy spaces in the pores and produce secondary cementitious material, which would increase the density, thereby increasing the strength. The results showed that the slag-integrated hempcrete (M3) was better than the other mixes. The mix resulted in strengths of 21.32 MPa and 31.75 MPa for the 7th and 28th day of testing. The mix had both the hemp and slag, which resulted in

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enhanced strength. The secondary cementitious material due to slag and higher friction yielded higher strengths. The values for the compression strength are tabulated in (Table 4).

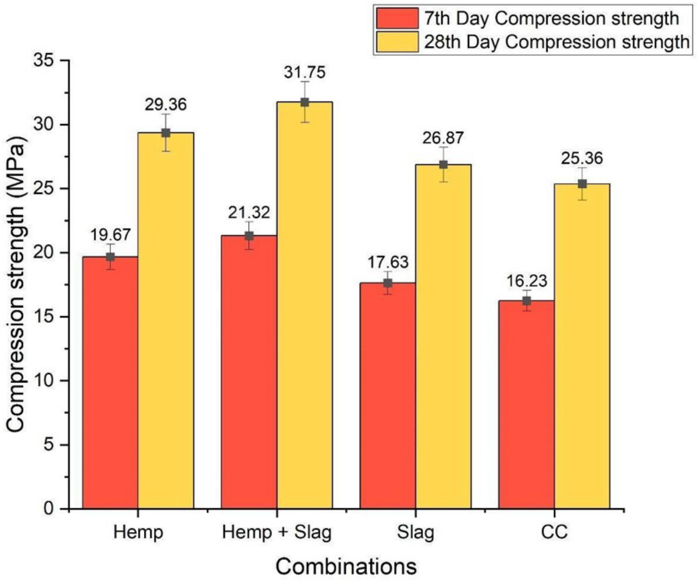

Figure 3. Compression strength results after curing.

Table 4. Compression strength values for all mixes of the study.

Description	7th day strength (MPa)	28th day strength (MPa)
CC	16.23 ± 0.81	25.36 ± 1.26
M1	19.67 ± 0.98	29.36 ± 1.46
M2	17.63 ± 0.88	26.87 ± 1.34
M3	21.32 ± 1.06	31.75 ± 1.58

4.2 Testing of specimen – Flexure strength

The flexure strength of the specimens showed similar behavior to the compression testing as illustrated in (Figure 4) (with 5% error bars). CC showed the least flexure strength of 2.47 MPa and 3.53 MPa for the 7th and 28th day, respectively. The hempcrete (M1) exhibited strengths of 2.63 MPa and 3.92 MPa, while the slag-integrated concrete (M2) resulted in 2.57 MPa and 3.78 MPa for the same periods of curing. The slag-integrated hempcrete (M3) resulted in higher strengths of 2.95 MPa and 4.21 MPa for the 7th and 28th day of testing. The hemp creates more friction, and slag enters the pores of bigger materials, resulting in better strength than the other mixes. The values for the flexure strength are tabulated in (Table 5).

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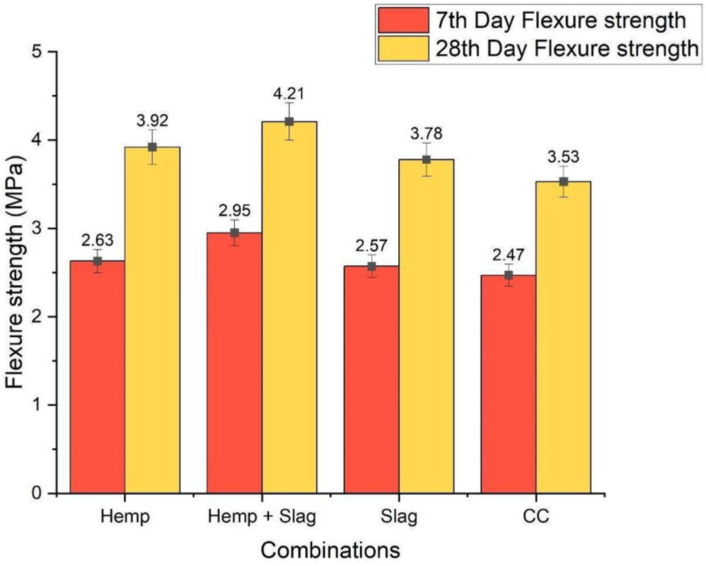

Figure 4. Flexure strength results after curing.

Table 5. Flexure strength values for all mixes of the study.

Description	7th day strength (MPa)	28th day strength (MPa)
CC	2.47 ± 0.12	3.53 ± 0.17
M1	2.63 ± 0.13	3.92 ± 0.19
M2	2.57 ± 0.12	3.78 ± 0.18
M3	2.95 ± 0.14	4.21 ± 0.21

4.3 Testing of specimen – Water absorption

The durability tests were more significant than the strength testing since the structure needs to be resilient for its lifecycle. The first test that was done to measure the durability was the water absorption of the specimen. The results of the water absorption test are demonstrated in (Figure 5). The water absorption of the M3 was the least, resulting in 3.54% after the testing. This would be the result of slag occupying the pores of the bigger aggregates, increasing the density and absorption of water into the structure (Rameshkumar and Vaishnavi Devi, 2023). M2 mix had a water absorption of 3.73% owing to the action of slag inside the pores. The hempcrete (M1) had a 3.95% water absorption and was the highest, barring conventional concrete. The reason for higher absorptions could be the size of the hemp, which was bigger than the slag. The increase in the size of the hemp resulted in higher voids, which increased the absorption of water. Concrete showed the highest water absorption of 4.53% of all the configurations. The values for the water absorption are tabulated in (Table 6).

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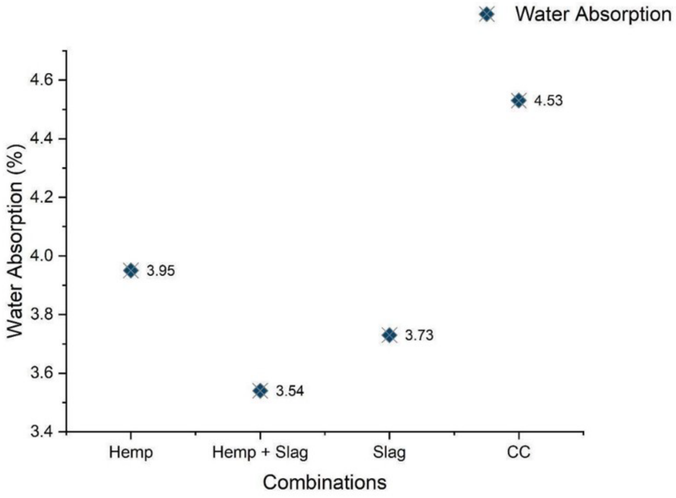

Figure 5. Water absorption results after testing.

Table 6. Water absorption for all mixes of the study.

Description	Water Absorption (%)
CC	4.53
M1	3.95
M2	3.73
M3	3.54

4.4 Testing of specimen – Acidic environment test

The specimens were kept inside an acidic environment to test the penetration of acid into the core structure. The specimens were taken out on the respective days and tested for compression to show the level of reduction of compression strength. The acidic environment produced a drastic reduction in strength for conventional concrete, as shown in (Figure 6) (with 5% error bars). CC showed a reduced strength of 12.36 MPa from an initial strength of 25.36 MPa, reducing by 51.26%. The M1 mix showed a compression strength reduction of 49.89%, which was not ideal. The initial strength has reduced owing to the porous structure of hempcrete compared to the other mixes. The M2 mix had a reduction of 46.55%, which is better than the previous mixes. The best one among the mixes was slag-integrated hempcrete (M3), resulting in 44.44%. All the mixes had a compression strength reduction above 40%, which was not ideal for any structure.

The present mix design (M25) is highly workable and would result in higher pores. The target mean strength could be increased in future studies for better resistance to acidic environments. The values for the flexure strength are tabulated in (Table 7).

Table 7. Reduction of Compression strength for all mixes of the study.

Description	After 7 days of immersion (MPa)	After 14 days of immersion (MPa)	After 28 days of immersion (MPa)
CC	21.37 ± 1.06	17.76 ± 0.89	12.36 ± 0.62
M1	25.14 ± 1.25	19.27 ± 0.96	14.76 ± 0.74
M2	23.68 ± 1.18	18.73 ± 0.93	14.36 ± 0.72
M3	26.38 ± 1.32	20.91 ± 1.04	17.63 ± 0.88

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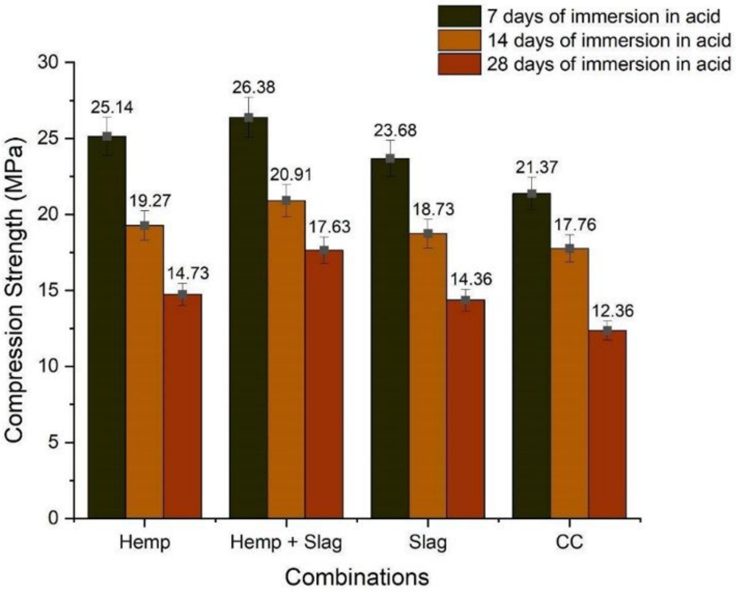

Figure 6. Acidic environment test results.

4.5 Testing of specimen – Microstructure Analysis

The microstructure of the hempcrete integrated with slag was seen at various magnifications for a better understanding of the core structure. The mix containing both slag and hemp was used for the microstructure analysis is illustrated in (Figure 7).

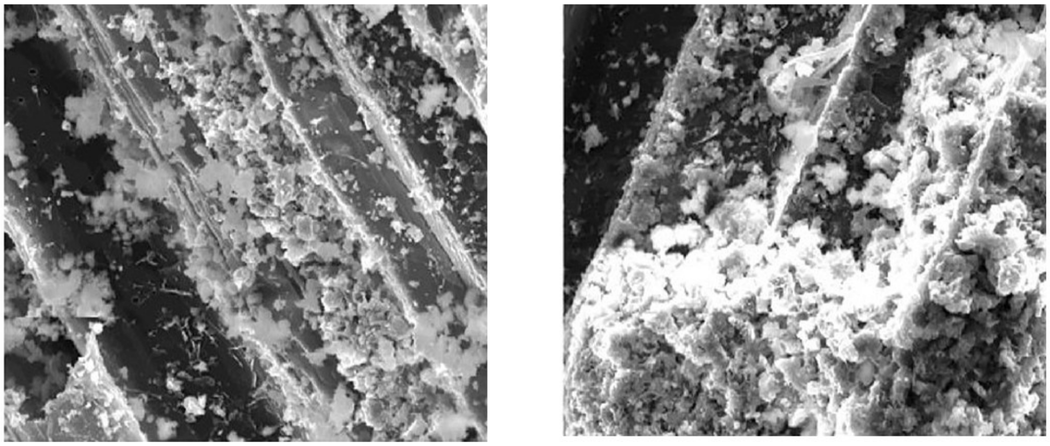

Figure 7. FESEM images taken at 20µm showing the presence of slag and hemp fibre.

The slag occupied the pores of the hemp and the aggregates, increasing the density and, consequently, the overall strength. The reduction of voids also enhanced the durability properties of the mix. The hemp also increased the binding property, resulting in better friction and strength. The slag-integrated concrete entered the pores and reduced the permeability of the mix. In comparison to the other two mixes, this mix exhibited superior durability attributes, which might be attributed to the reduction of porosity. At the same magnification, the hempcrete had higher voids, which resulted in reduced durability qualities. Conventional concrete suffered from higher porosity values, leading to the least durable mix of all the available options. The above images visually confirm the reduced pores inside the core concrete, increasing its strength and durability properties.

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5. Conclusions

A study on the strength and durability properties of slag and hemp integrated into concrete was conducted. Four mixes, Conventional concrete (CC), Hempcrete (M1), slag-integrated concrete (M2) and slag-integrated hempcrete (M3) were utilized for the study, and the following conclusions were observed.

- Conventional Concrete (CC) has the lowest compressive strengths of 16.23 MPa and 25.36 MPa after the 7th and 28th days of curing. Hempcrete (M1) resulted in strengths of 19.67 and 29.36 MPa after 7 and 28 days of curing. The 7th and 28th day strength of slag-integrated concrete (M2) was 17.63 and 26.87 MPa. The best mix was slag-integrated hempcrete (M3), resulting in 21.32 and 31.75 MPa at the 7th and 28th days of testing. The secondary cementitious material due to slag and higher friction yielded higher strengths for the M3 mix.

- Similar results were seen in the flexure testing, in which CC had the lowest flexure strength at 2.47 MPa and 3.53 MPa for 7th and 28th-day strength. The M1 mix exhibited strengths of 2.63 MPa and 3.92 MPa, while the M2 mix had 2.57 and 3.78 MPa for the strength on the 7th and 28th day. The slag-integrated hempcrete (M3) showed 2.95 MPa and 4.21 MPa on the 7th and 28th day respectively, due to secondary cementitious material along with higher friction.

- The water absorption testing showed that slag-integrated hempcrete (M3) absorbed the least water, 3.54%. Slag-integrated concrete (M2) absorbed 3.73%, while hempcrete (M1) resulted in 3.95% absorption. CC showed the highest water absorption value of 4.53%.

- Conventional concrete (CC) resulted in a 51.26% reduction in compressive strength. Hempcrete had a 49.89% compression strength reduction, while Slag-integrated concrete reduced 46.55%. The best mix was slag-integrated hempcrete, resulting in a compressive strength reduction of 44.44%. The reduction of compressive strengths after interaction with the acidic environment was not ideal for any mix and has to be designed for higher grades in future work.

- FESEM images show that Hemp fibre could reduce friction-induced deformations and enhance load transfers while slag occupies pores and produces secondary cementitious materials, increasing density and indirect strength.

6. Future Work

The concrete mix grade used in the present study resulted in a drastic reduction in the compression strength when it was exposed to acidic environments. Future studies can experiment with higher grades of concrete for better performance in resisting acidic penetration.

7. Notes on Contributors

Vighnesh Rameshkumar, Department of Civil Engineering, Kumaraguru College of Technology, Coimbatore, Tamilnadu, India. **ORCID** https://orcid.org/0000-0002-3730-7167	**Vaishnavi Devi S.,** Department of Civil Engineering, Thiagarajar College of Engineering, Madurai, Tamilnadu, India. **ORCID** https://orcid.org/0000-0002-3726-2085

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