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EVALUATION OF PHYSIOCHEMICAL PROPERTIES AND MICROSTRUCTURE OF CEMENT PASTE BLENDED WITH SAPONIFIED COOKING OIL AND CETRIMONIUM CHLORIDE

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ABSTRACT

Sustainable development relies on recycling environmental resources, which includes the recycling of liquid and solid wastes by using them as obtained or after treatment. One such environmentally burdensome material is the used cooking oil, which this study examines after its treatment through saponification and blending with CTAC as a cationic surfactant. The study evaluated five cement paste mixes with different concentrations, ranging from 0% to 5% of saponified cooking oil (SCO). The results pointed out that SCO enhanced the workability and air content (0-30%) but therefore reduced density (2.0-1.39 g/cm³), thermal conductivity (0.72-0.25 W/m•K), and compressive strength (72.7-32.22 N/mm²) as a result of increasing porosity. On the other hand, water absorption decreased by 69% at 1%. SCO outperforms traditional foam cement due to SCO's hydrophobicity. Microstructural analysis (SEM) shows a homogeneous distribution of air voids in the cement paste matrix (~63.1 µm). The cement pastes with SCO dosages (1-5%) were blended with 1% cetrimonium chloride cationic surfactant (CTAC). The results show an increase in the air content (up to 49.5%) and therefore a reduction in density down to 1.010 g/cm³, thermal conductivity (0.20 W/m•K), and compressive strength (15.4 N/mm²) as a result of increasing porosity. On the other hand, water absorption increased about eight times compared to the reference sample at (5% SCO + 1% CTAC) due to high porosity. In conclusion, the utilization of SCO admixture resulted in a significant alteration in the performance of cement pastes. The addition of SCO has a positive effect on cement paste's permeability-related properties by reducing the water absorption into the hardened cement pastes, improving thermal insulation, and making them especially suitable for lightweight construction materials where moisture control is critical. Still, their mechanical characteristics are slightly decreased but within acceptable limits in these cases. These findings highlight the unique behavior of saponified cooking sunflower oil used in cement matrices. When 1% CTAC is blended into the SCO cement mix, the thermal insulation is improved due to the increase in the air content, but this addition reversely affects both compressive strength and water absorption, and remains in the acceptable range for a non-constructive building material.

Keywords: cement paste, saponified cooking oil, cetrimonium chloride (CTAC), physiochemical properties, microstructure, sustainable construction materials, green additives, compressive strength, pore structure, surface-active agents.

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INTRODUCTION

Waste oil includes waste resulting from human activity in homes, restaurants, industrial facilities, and cars. (Liu *et al*., 2020). Due to repeated frying, sunflower oil contains a certain number of carcinogens, such as benzopyrene, that will cause dangerous environmental pollution and health threats (Abousnina *et al*, 2020). The amount of sunflower oil available globally is about 22.11 million metric tons per year (Awogbemi *et al*., 2019). At present, the recycling of sunflower oil is mainly in biodiesel (Buczek, 2014; Liu *et al*., 2018), bio-lubricant (Karmakar *et al*., 2017), animal food (Tres *et al*., 2013), and soap production (Maotsela *et al*., 2019), but only a small percentage is recycled due to the expensive and complicated processes (Foo *et al*., 2022). Therefore, discovering the value-added recycling of sunflower oil is imperative and highly desirable (Abdelzaher *et al*., 2023; Abdelzaher and Awad, 2022). Given the enormous annual global consumption of cement concrete, concrete could be an ideal matrix for recycling such waste (Abbas *et al*., 2024; Abbas *et al*., 2021)

Some researchers studied the value of waste of sunflower oil as an admixture in the industry of building materials, such as in asphalt concrete and shrinkage reducers and water repellents (Libessart *et al*., 2023), crack inhibitors (Liu *et al*., 2020) in cement concrete, and phase change capsules (Chen *et al*., 2024) in foamed concrete. Vejmelkov *et al*. (2012 reported that waste oil significantly reduced the water absorption of lime metakaolin mortars, which is widely believed to be due to the increase in pores' hydrophobicity caused by oil (Nunes *et al*., 2018). Studies have also reported that 2 % waste oil by cement weight effectively reduced shrinkage of concrete (Han *et al*., 2014), which was caused by the saponification reaction between oil and calcium hydroxide in cement solution. Liu *et al*. (2020 found that 0.6% sunflower oil waste by aggregate weight can reduce the drying concrete shrinkage by 5.8 %-13.6 %. However,

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adding waste oil to mortar usually reduces the compressive strength (Vejmelková *et al*., 2012). Baghban *et al*. (2012 showed that 1 % rapeseed oil reduced the strength of cement paste by 6 %-14 %. Thus, based on the reported studies, it can be concluded that the effect of waste cooking oil on cement paste properties is not always favorable; therefore, it is necessary to investigate its effect before using it to minimize adverse effects. In this context, researchers have studied the pore structure of waste oil-based mortars. Nunes and Slížková (2014) reported that 1.5 % vegetable oil resulted in a significant porosity increase for lime-metakaolin mortars. Cechova *et al.* (2009 found that 1 % vegetable oil decreased porosity, whereas 3 % vegetable oil increased porosity of cementitious materials. Based on previous studies, the percentage of oil waste added to the cement paste affects the physical properties, but the matter requires further study. However, there is a lack of in-depth analysis; that is why this study aims to reveal the effects of saponified cooking oil and saponified cooking oil blended with cetrimonium chloride on the workability, microstructure, air content, density, compressive strength, water absorbance, and thermal insulation of cement mortar and its correlation with macroscopic properties.

MATERIALS

a) Ordinary Portland Cement (OPC) (CEM I 52.5N) was obtained from El Arish Cement Factory. Table-1 contains its chemical composition as supplied by the factory.
b) The used cooking sunflower oil key physicochemical characteristics are listed in Table 2.
c) Potassium hydroxide (KOH) was purchased from Merck and used to prepare a 0.1 M potassium hydroxide (KOH) solution.
d) Admixture: Cetrimonium Chloride (CTAC), a commercial-grade surfactant used as an admixture purchased from Lerochem and used as received, as given in Table-3.

Table-1. The chemical composition of the used Ordinary Portland Cement (OPC).

Oxide	SiO2	Al2O3	Fe2O3	CaO	Na2O	K2O	Cl-	MgO	SO3	Free CaO	Ignition Loss
(%)	22.12	5.56	3.69	62.87	0.26	0.11	0.02	2.36	0.91	0.92	1.22

Table-2. Physicochemical properties of sunflower oil (before and after cooking).

Property	Before Cooking	After Cooking
Density (g/cm³) at 20°C	0.912	0.926
Refractive Index at 20°C	1.461	1.474
Saponification Value (mg KOH/g oil)	191	189.5
Iodine Value (g I_2/100 g oil)	136	133.5
Acid Value (mg KOH/g oil)	2.10	3.70
Peroxide Value (meq O_2/kg oil)	0.77	6.80

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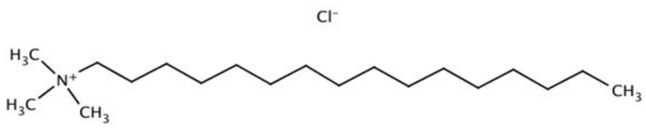
Table-3. Specification of cetrimonium chloride solution.

Parameter	Attribute
Chemical Name	Cetrimonium Chloride, Cetyltrimethylammonium Chloride
Chemical Formula	$C_{19}H_{42}ClN$
Molar Mass	284.5 g/mol
Density	0.95 g/cm³ (at 20 °C)
Solubility	Miscible in water
Physical State	Typically available as a 30% aqueous solution
Grade Used	Commercial Grade
pH at 25C^0	6-8
Character	cationic surfactant
Appearance	Clear colorless liquid
Structure	

TECHNIQUES AND INSTRUMENTATION

Oil Collection and Filtration

The used sunflower cooking oil was collected from the researcher's home in Gaza, Palestine. The impurities were purified using three steps: the first was gravity precipitation to separate large impurities, then filtration using a 150-micrometer sieve, and finally vacuum filtration to remove impurities less than 150 micrometers. All the treated samples of used cooking oil will be stored in plastic drums.

Saponification of Used Cooking Oil

The used cooking oil was partially saponified under cold conditions using 0.1 M KOH with continuous stirring at 200 rpm for 30 minutes. Approximately 20% of the oil remained unreacted, and the pH of the reaction medium at 25 °C was about 8. The resulting Saponified Cooking Oil (SCO) was subsequently utilized in the preparation of cement paste samples.

Paste Preparation

0-5% from the weight of cement of SCO dissolved in 650 g of H_2O and added to different doses of SCO ranging from 1 to 5% to and then added to 1500 g of cement; W/C is 0.43.

1% Cetrimonium Chloride (CTAC) from the weight of cement dissolved in 650 g of H_2O and added to another different dose of SCO, ranging from 1 to 5% to and then added to 1500 g of cement; W/C is 0.43 as recommended (Qaraman, 2016).

The sample mixing was carried out under continuous and vigorous stirring for about three minutes. After complete mixing, the resulting paste is poured into 12 cm × 4 cm × 4 cm molds. The molds were kept at about 100% relative humidity at room temperature for one day. The hardened cement pastes are then removed from the molds after they attain the final setting and cured under water for the rest of the hydration ages (up to 28 days).

Consistency and Setting Times of Cement Paste

The consistency and setting times of cement paste were measured by the Vicat apparatus as per the requirements of BS EN 196-3.

Compressive Strength

Three specimens of each mix at different hydration times (3, 7, and 28 days) are used for compressive strength testing using a point load tester (20063 cemasco S/N-Controls type, Milano, Italy). The mean value of the three specimens at each hydration age was considered. ASTM C109/C109M-21.

Stopping of Hydration

10 g of the crushed hardened pastes after performing a compressive strength test was put into a beaker containing 100 ml of acetone/ethyl alcohol (1:1 by volume) to stop the hydration process. The mixture was stirred for 0.5 hr. The residue was filtered off, washed with ethanol, and dried at 50°C for about 24 hrs. The dried samples were then stored in a desiccator for the following physical analysis.

Determination of the Bulk Density and Air Content of the Cement Pastes

The bulk density and air content were determined by measuring the weight of the sample in air (W air) and under water (W water). The density (ρ) in g/cm³ was then

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calculated as mentioned in ASTM Standard C 138-08 - 2008 using the formula:

Air content was derived from the theoretical density of air-free paste and the measured bulk density.

$$\rho = \frac{\text{W air}}{\text{W air} - W\ water} \times \rho\ water$$

Thermal Conductivity Measurement

Thermal conductivity (k) was examined via the steady-state guarded hot plate method (ASTM C177). Ten disc-shaped samples (130 mm diameter × 30 mm thickness), two per mix, were prepared. The thermal conductivity coefficient was calculated as:

where:

- k = Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$),
- qx = Heat flux (W·m−2),
- x = Sample thickness (m),
- ΔT = Temperature gradient across the sample (°C).

$$k = \frac{qx\,.\,x}{\Delta T}$$

Scanning Electron Microscopic (SEM) Measurements

The morphology and microstructure of the dried hydrated samples were studied using a JEOL JXA 840 electron probe microanalyzer SEM. The specimens were coated with a thin film of gold under a vacuum evaporator with cathode rays and then analyzed.

Water Absorption Test

Water absorption was calculated according to ASTM C642. The specimens were dried at 105°C for 24 hours to determine the dry mass (M0), and then the specimens were immersed in water for 24 hours, and the saturated mass (M1) was recorded. Water absorption (WA) was calculated as:

$$WA(\%) = \frac{M1 - M0}{M0} \times 100$$

RESULTS AND DISCUSSIONS

Effect of SCO on the Consistency of Cement Paste

Cement paste consistency with varying SCO and (SCO + 1% CTAC) dosages is shown in Table-4. The consistency of the 0% cement paste is within the standard range of 27 to 33%, but the additives made the paste more consistent. The paste with SCO reached the highest consistency of 35.50% at the 5% dosage, and (SCO + 1% CTAC) reached the highest consistency of 35.80% at the 5% SCO + 1% CTAC dosage.

We note that adding 1% CTAC improved the dispersion due to its ability to stabilize microscopic air voids in the matrix, which slightly improved the consistency and increased workability compared to SCO alone.

This can be explained by the fact that SCO alone reduces consistency due to its water-repelling properties, high viscosity, and potential water consumption, while the addition of a CTAC begins to counteract this effect. The higher doses of SCO (2.5- 5%) blended with 1% CTAC improve lubricity and air retention, resulting in better flow.

Table-4. Consistency of cement paste with different dosages of admixtures.

Admixture Dosage (%)	SCO Consistency (%)	SCO + 1% CTAC (%)
0.0	33.00	33.00
1.0	34.20	34.80
1.5	34.70	35.30
2.5	35.20	35.70
5.0	35.50	35.80

Table-5. Result for the initial and final setting time of cement paste.

Admixture Dosage (%)	SCO - Initial (hr:mm)	SCO - Final (hr:mm)	(SCO + 1% CTAC)- Initial (hr:mm)	(SCO + 1% CTAC) - Final (hr:mm)
0.0	1:58	6:19	2:00	6:30
1.0	2:00	5:10	2:20	6:00
1.5	2:18	6:40	2:45	6:30
2.5	2:45	6:30	3:30	7:00
5.0	2:55	7:15	4:30	7:45

The initial and final setting times indicate the hydration behavior and the transition of cement paste from the liquid state to the beginning of setting and the formation of hardened cement. Table-5 shows the effect of increasing SCO dosage in cement paste from 1% to 5%, regardless of being added independently or mixed with 1% CTAC. The initial and final setting times are significantly prolonged with increasing SCO dosage, indicating that

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early cement hydration is inhibited by the interaction of the cement with both SCO and CTAC.

The results show that the initial setting process is delayed by approximately three hours when 5% SCO is added alone and at 4.5 hours when the (5% SCO + 1% CTAC) mixture is added. The final setting time is gradually delayed to 7 hours and 15 minutes for 5% SCO alone and 7 hours and 45 minutes for the (5% SCO + 1% CTAC) mixture.

This retardation can be explained by the fact that the saponified oil contains fatty acids that can react with calcium ions (Ca^{2+}) in the cement paste. The reaction products coat the cement grains and impede water from penetrating them, retarding the hydration process and, consequently, initial and final hardening.

CTAC has a dual role: as a surfactant, it stabilizes air bubbles formed during mixing, reducing direct contact between water and cement. On the other hand, it acts as a dispersant due to the repulsion of the positive charges it carries with the positive charges on the calcium ions surrounding the cement grains, while simultaneously slowing the rate of C-S-H growth .

The results in Table-5 also show that the final setting time is gradually delayed to 7 hours and 15 minutes in the case of 5% SCO alone and to 7 hours and 45 minutes in the case of the (5% SCO + 1% CTAC) mixture. Once again, the additives, either individually or in combination, slow the complete hydration reaction. This can be explained by the fact that both SCO and CTAC, separately or together, limit the growth of hydration products such as Ettringite crystals and C-S-H bonds, which are responsible for final hardening. The higher the concentration of these substances, the greater their cumulative effect. As a result, both SCO and CTAC act as retarders of the chemical reaction between water and cement, but their mechanism are different, and their combined effect results in a significant delay in setting time.

Effect of SCO on Air Content and Bulk Density

Air content is the controlling factor that affects other characteristics of the cement paste (i.e., density, compressive strength, insulation, water absorbance, and workability).

The results in Table-6 for (M0-M4) mixes/ indicate the SCO efficiency as an air-entraining agent, with the air content gradually increasing from 0 to 30% as the dosage increased from 0 to 5%. This resulted in a significant decrease in density from 2 g/cm^3 to 1.39 g/cm^3. This behavior can be explained by the SCO surfactant properties.

Table-6 and Figures 1 and 2 also show the behavior of cement pastes for mixtures (mix 1–mix 4) with the addition of 1% cationic surfactant CTAC to the saponified oil. The addition of CTAC led to an enhancement of the air content in the cement mixtures. The highest percentage of air input (49.5%) is recorded for a mix 4 (5% SCO + 1% CTAC), which led to a dramatic decrease in density to 1.01 g/cm^3, which represents a decrease of approximately 50% compared to the density of the reference sample.

CTAC, as a cationic surfactant, has positive quaternary nitrogen that enhances the dispersion of air bubbles and cement grains. (Qaraman, 2019). The electrostatic repulsion between positive ions (Ca^{+2}) on the surface of cement grains and the CTAC molecules' positive charge keeps bubbles and cement grains separated; this leads to media expansion (dispersion action).

Both CTAC and SCO molecules are surfactants; their molecules are inserted between adjacent molecules at the water surface, and the mutual attraction between the separated water molecules is reduced. Lowering the surface tension stabilizes the bubble against mechanical deformation and rupture, making it easier for bubbles to be formed and therefore increasing the air content.

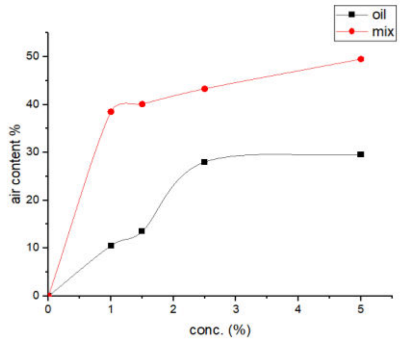

Figure-1. Relationship between SCO concentration and air content in hardened cement paste at 28 days.

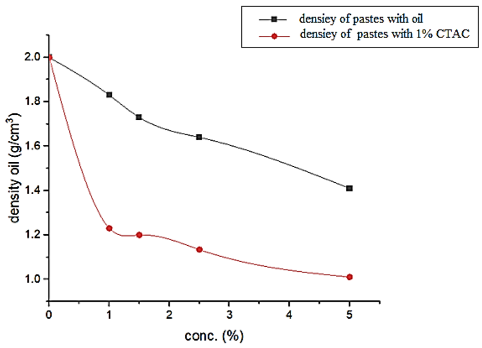

Figure-2. Relationship between bulk density and concentration of SCO-modified cementitious pastes at 28 days.

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Table-6. Composition and properties of foam cement paste mixes.

Mixture	Cement / water	Oil %	CTAC %	Density (gm/cm3)	Air %	Compressive Strength (N/mm^2)			Water Absorption %	Thermal conductivity W/m.k
						3 days	7 days	28 days		
M0	0.43	0	0	2.0	0.0	40.3	50.1	73	2.1	0.72
M1	0.43	1	0	1.78	11	39.10	48.9	71.2	0.65	0.32
M2	0.43	1.5	0	1.71	14	34.12	46.45	54.89	0.69	0.28
M3	0.43	2.5	0	1.41	28.5	27.98	35.33	51.71	0.74	0.26
M4	0.43	5	0	1.39	30	17.71	22.748	32.22	0.82	0.25
Mix1	0.43	1	1	1.23	38.5	13.41	16.76	24.18	9.03	0.23
Mix2	0.43	1.5	1	1.20	40.5	12.43	15.65	22.23	11.4	0.22
Mix3	0.43	2.5	1	1.134	43.3	11.93	14.90	21.50	13.2	0.21
Mix4	0.43	5	1	1.010	49.5	5.55	9.67	15.4	16.2	0.20

Effect of SCO on the Compressive Strength of the Hardened Cement Paste

The compressive strength values of cement pastes with different mixes and different hydration ages (3, 7, and 28 days) were determined; three specimens of each mix at each hydration time were used. The mean value is considered the compressive strength of the three specimens at each hydration age. 3, 7, and 28 days compressive strength of the mixes with 0-5% of SCO, besides four mixes of 0-5% of SCO with 1% CTAC cationic surfactant are shown in Table 6 and Figure-6. The results indicate that the compressive strength values of all mixes are directly proportional to the progress of the hydration time, which is due to the progress of the cement hydration reaction and an increase in the CSH network. The maximum values of compressive strength are achieved, in all cases, after 28 days of hydration.

Figure-6 shows that the compressive strength was inversely proportional with SCO dosages reaches its minimum value at 5% (M4) for all times (32.22 N/mm2 at 28 days), the addition of CTAC leads to more decline in the compressive strength and reached the lowest value for the Mix 4 (5% SCO + 1% CTAC) (15.4 N/mm2 at 28 days). This decrease in the compressive strength by increasing the SCO content can be explained mainly by the increase in the air content of all samples, as the air voids weaken the strength of cement pastes. These pastes, despite their low compressive strength, are acceptable for use in non-structural applications.

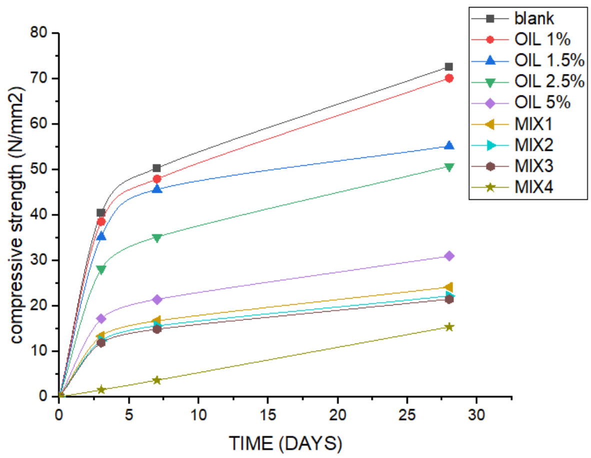

Figure-3. Compressive strength development of SCO-modified cementitious pastes at 3, 7, and 28 days of hydration.

Effect of SCO Doses on Thermal Conductivity of Hardened Cement Pastes

Energy-efficient materials are widely used in the construction sector to conserve energy while maintaining the quality of traditional materials. This reduces the energy required to maintain thermal comfort in homes throughout the year. This thermal comfort has positive economic benefits, including savings on electricity bills, as well as environmental benefits, including reducing harmful emissions that cause global warming. Foamed cement and foamed concrete are building materials that provide excellent thermal insulation due to their porous structure and the presence of insulated air bubbles, which reduce the material's density and increase its resistance to thermal conductivity.

As shown in Table-3 and Figure-7, the thermal conductivity of cement paste mixes is inversely proportional to the sulfur dioxide dosage. The results show that the thermal conductivity sharply decreases from M0

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to M4. The control mix (M0) exhibited the highest thermal conductivity (0.72 W/m•K), while the 5% SCO (M4) achieved the lowest thermal conductivity of 0.25 W/m•K. After blending the SCO mixes with 1% CTAC, the air entrainment increased, and as a result, the thermal conductivity decreased, reaching its minimum of 0.20 W/m•K for Mix4 (5% SCO + 1% CTAC).

This reduction is believed to be attributed to increased air content, which increases the porosity and introduces thermally insulating voids within the matrix.

The results of the study are consistent with the general behavior of foamed cement, which is also known as foamed concrete and is one of the materials in the lightweight category. It was discovered that its structure plays an important role in providing great thermal insulation performance. It has a low density between 300 kg/m^3 to 1600 kg/m3 and thermal conductivity properties between 0.10 W/m.K to 0.66 W/m.K. (Rommel, Rejlekova, & Kozlovska, 2020).

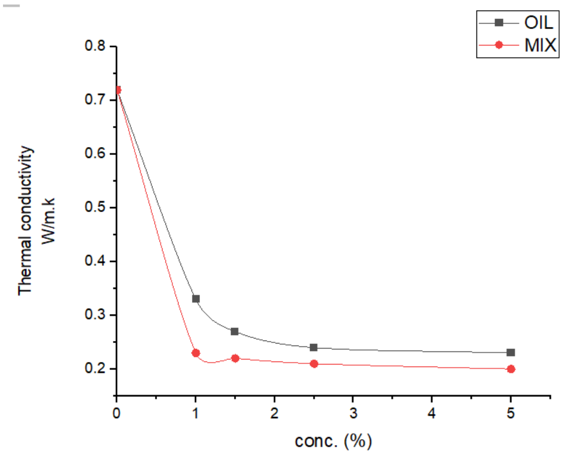

Figure-4. Inverse correlation between thermal conductivity and concentration of SCO-CTAC modified cementitious pastes after 28 days of hydration.

The Morphology and Microstructure Effects of the Addition of SCO on the Hardened Concrete

The scanning electron microscope (SEM) is a good tool for chemical analysis and imaging in cement pastes and concrete. Its high resolution enables a detailed study of the surface topography of the rough surfaces of e.g., the formed calcium silicate hydrate (CSH) and calcium hydroxide (CH). The graphs of different mixes of hardened cement pastes after 28 days are shown in Figures (5 -7).

Figure 5 (a-e) shows the graphs (10× magnification) of the hardened cement pastes for different mixes with SCO (M0-M4), whose doses ranged (1-5%), after 28 days of hydration. The images illustrated the surface morphology of hardened cement pastes with tiny, uniform, and consistent air void systems; these voids increased with increasing concentration of SCO. Figure 10 shows the effect of adding 1% CTAC to different SCO mixes (Mix1- Mix 4). From the graphs, it's clear that the voids increased and became larger, and increased with some connectivity between voids.

For a deeper study of the development of the hydration reaction in cement paste, the M0, M4, and Mix 4 were chosen, which showed the greatest results to study the microstructure at 5000× magnification.

Figure-7(a-c) shows images of the hardened cement pastes of M0, M4, and Mix 4 after 7 days of hydration. It is possible to observe the appearance of hexagonal calcium hydroxide lamellae alongside the fibrous CSH phase. Figure 5 (b-c) shows large gaps with hexagonal calcium hydroxide lamellae alongside the CSH phase.

Figure-7(d-f) shows images of the hardened cement pastes of M0, M4, and Mix 4 after 28 days of hydration. It is possible to observe that the hydration products appeared more compact and consisted of calcium silicate hydrates, which explains the improved strength at 28 days for all mixes.

On the other hand, the structure of cement paste with the addition of SCO produced a consistent bubble structure with a uniform and homogenous bubble structure with air voids (~62.4 µm), but after the CTAC addition, the bubbles became slightly larger with air voids (~82.4 µm).

These results are consistent with the findings of previous studies that showed that the microstructure of mixed cement pastes was affected, leading to an acceleration of the hydration reaction, improvement of the microstructure, and increased porosity. (Alnuaimi, Al-Jabri, & Al-Saidy, 2020).

Figure-5. Macroscopic surface morphology of hardened cement paste specimens at 28 days of hydration (10× magnification):(a) Control sample (0% SCO), (b) 1% SCO. (c) 1.5% SCO (d) 2.5 % SCO (e) 5% SCO.

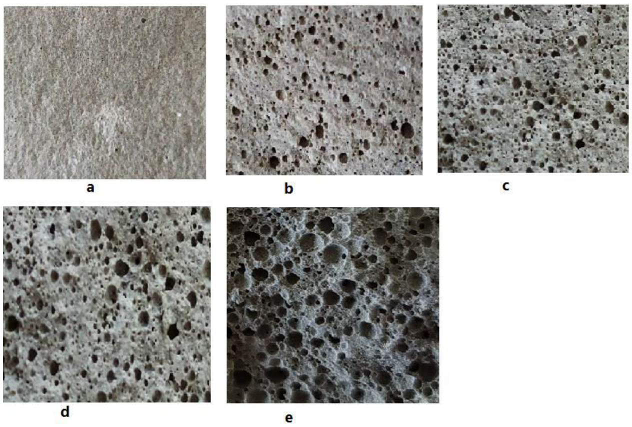

Figure-6. Macroscopic surface morphology of hardened cement paste specimens at 28-day Mix s of hydration (10× magnification): (a) Control sample (0% SCO), (b) Mix 1 (c) Mix 2 (d) Mix 3 (e) Mix 4.

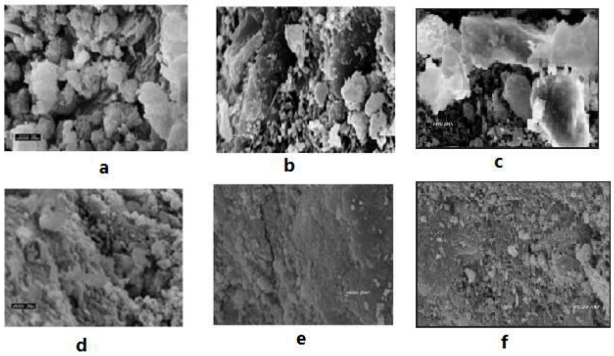

Figure-7. Scanning electron microscopy (SEM) images of hardened cement pastes at 5000× magnification:
(a) Control sample (0% SCO) and (b) 5% SCO (c) (5% SCO+1%CTAC) after 7 days of hydration.
(d) Control sample (0% SCO) and (e) 5% SCO (f)) (5% SCO+1%CTAC) after 28 days of hydration

Effect of SCO on the Water Absorbance of Hardened Cement Paste

Water absorption is a significant durability indicator for hardened cement pastes, especially in foamed cementitious mixes where porosity plays a key role. The fundamental criteria for selecting any oil as a water-repellent admixture are referred to in its content of monounsaturated fatty acid; as a high unsaturated fatty acid, vegetable oil performs better in a cement paste matrix (Justnes, 2008).

The results in Table-3 and Figure-8 demonstrate a decrease in water absorption for all cementitious mixes containing the SCO admixture. Reaching the lowest value of 0.65% at 1% SCO content (M1), compared to 2.1% for the control mix (M0, 0% SCO). By increasing the SCO content to 5% (M4), water absorption slightly rises to 0.82% but remains substantially below the control value. Water absorption is expected to decrease naturally with the use of SCO due to the hydrophobic nature of the saponified oil, especially since the cold saponification process is not complete, and unsaponified fatty acids remain, which increase the hydrophobic properties of the cement paste.

Water absorption is expected to decrease naturally with the use of SCO due to the hydrophobic nature of the saponified oil, especially since the cold saponification process is not complete, and unsaponified fatty acids remain, increasing the hydrophobic properties of the cement paste. In addition, the SEM images showed that the introduced voids are small and separate, which prevents water from moving by capillary action within the system.

However, when the CTAC is added to the mixes (Mix1- Mix 4), the entrained air content is increased, and as a result, greatly raises the porosity and the absorptions (9.03%-16.2%). The mixes (Mix 1- Mix 3) remain within acceptable limits for foam cement pastes, which often range from 5% to 15% due to their porous structure, but Mix 4 exceeds this limit slightly. (Eires, Camões, & Jalali, 2017). This significant increase in water absorption is attributed to the fact that the addition of CTAC to the SOC mixtures increased the air content up to 49.5%, and the voids became larger with increased interconnectivity of the voids, as is clear from the SEM images.

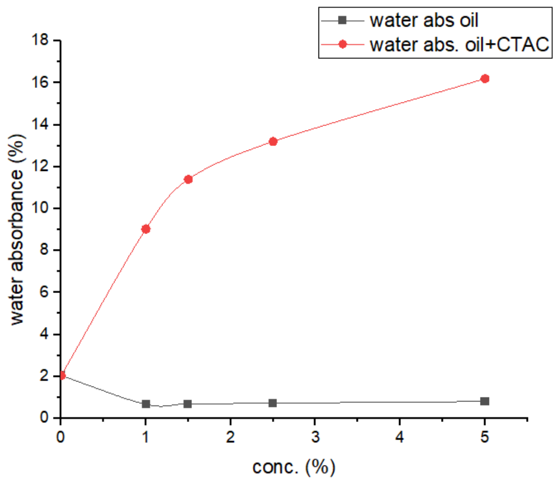

Figure-8. The relationship of concentration and water absorption of SCO cementitious pastes after 28 days of hydration.

CONCLUSIONS

In conclusion, the utilization of SCO admixture resulted in a significant alteration in the performance of cement pastes. The addition of SCO has proved to have a positive effect on cement paste's permeability-related properties by reducing the water absorption into the hardened cement pastes, improving thermal insulation, and making them especially suitable for lightweight construction materials where moisture control is critical, but their mechanical characteristics are slightly decreased, within acceptable limits in these cases. These findings

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highlight the unique behavior of saponified sunflower oil used in cement matrices. When 1% CTAC is blended into the SCO-cement mixes, the thermal insulation is improved due to the increase in the air content, but this addition reversely affected both compressive strength and water absorption, and remains in the acceptable range for a non-constructive building material.

Foam cement pastes have numerous applications in the construction field, and their appropriate properties depend on the application, taking into account the balance between strength, insulation, and water absorption. Mix M1 (1% oil) provided compressive strength close to that of the reference sample (71.2 N/mm²), with a significant improvement in thermal insulation (0.32 W/m·K) and a reduction in water absorption to 0.65%. Therefore, it can be used well for construction applications such as load-bearing walls. If thermal insulation is the desired property, such as non-load-bearing walls, Mix 4 (5% oil + 1% CTAC) is optimal, achieving the lowest thermal conductivity (0.20 W/m·K), but sacrificing strength (15.4 N/mm²) and increasing water absorption to 16.2%. Mixture M3 (2.5% oil) provides a moderate balance between strength, insulation, and water absorption, providing moderate compressive strength (51.71 N/mm²) and thermal conductivity (0.26 W/m·K), but sacrificing strength and water absorption to 0.74%, all within the limits permitted for non-structural uses.

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