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EVALUATING THE USE OF MUCILAGE FROM OPUNTIA FICUS-INDICA AS A BIO-ADDITIVE IN PRODUCTION OF SUSTAINABLE CONCRETE

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Abstract

The global demand for a sustainable and environmentally responsible economy, has called for incorporation of aspects of sustainability into infrastructure materials. Being the most globally consumed primary construction material, concrete's strength and durability enhancement using green approaches is pivotal to sustainability of the built environment. Production of chemical admixtures is high energy consuming and environmentally taxing, thus the need for bio-available sustainable substitutes and/or supplements. This paper presents findings of an experimental and environmental impact evaluation, conducted on Normal Strength Concrete (NSC) mixtures dosed with *Opuntia ficus-indica* mucilage (*Ofim*) by mass-replacement of the mixing water. ASTM compliant tests for consistency, strength, and durability performance were conducted at standard time intervals up to 56 days, while the Scanning Electron Microscopy (SEM) and Fourier Transform Infrared (FTIR) Spectroscopy were employed for concrete micro-characterization. The study explored the interaction between the natural bio-additive and synthetic commercial admixture. A comparative Environmental Life Cycle Assessment (E-LCA) was also conducted to assess resource use efficiency and quantify the environmental impacts of *Ofim*-modified concrete relative to conventional concrete. Test results showed that the use of *Ofim* led to slight increase in the compressive strength and elastic modulus, in addition to a pronounced impact on durability of concrete, resulting in reduced fluid ingress by up to 39%, a lowered decrease in K-values by 14%, and an increase in the freeze-thaw resistance with high retention of Relative Dynamic Modulus of Elasticity (RDME) in the *Ofim*-modified mix relative to the control mix. A 15% mixing-water mass-replacement resulted in an average reduction in greenhouse gas (GHG) emissions of 9.6%. Hence, even if the improvement in the mechanical performance is not substantial, a reduction in GHG emissions scales up as the concrete industry is huge and tremendously contributes to climate change through embodied carbon.

Key words: Bio-additive; mucilage; water mass replacement; sustainability; life cycle assessment.

1. INTRODUCTION

Following the urgent call by the UN Sustainable Development Goal (SDG) 11 for the development of resilient and sustainable cities and human settlements, the global construction industry has witnessed an exponential growth over the past decade [1]. Despite the stinging global economic crisis and shift in global investment priorities, the construction industry demonstrated resilience through a continued steady growth. It remains essential however, that the industry addresses the challenges posed by supply shortage, rising prices, and global shifts towards sustainable infrastructure, which will have a profound effect on its future growth [2]. Researchers in the construction industry have continuously invested enormous effort in attempts to optimize the construction cost, by investigating ways to partially or fully replace important but relatively costly construction materials, or through enhancement of material properties to incorporate sustainability aspects in the sector, aimed at minimizing life-cycle costs [3]. Concrete is the most consumed construction material universally, and hence a reduction in the cost of concrete without impairing its performance would emerge a registered success. This is being progressively achieved through concrete mechanical and durability property enhancement, using industrial or natural additives [2]. From the turn of the millennium, no sign of a fall or even decreasing rate in the demand of Portland Cement Concrete (PCC) was predictable, until 2020 when the ready-mix concrete industry registered a 40% drop in demand and consumption, evidently attributed to the Covid-19 pandemic [4-6]. PCC, the most produced synthetic material on earth, ranks among silicon, oil, and gas as the most pivotal facilitators of modern society development [6]. The trend of infrastructure development has been followed by a commensurate rise in concrete production, leading to massive exploration of natural resources for concrete aggregates and production of cement, concrete's binder material. By 2020, the global annual production of cement was estimated at 4.4 billion metric tons, exceeding even the earlier 2050 per annum forecast of 4 billion metric tons. At such rates of production, cement ranks as the most globally produced industrial material on earth by mass, and the second most consumed substance after water [7].

It is forecasted that in the next 50 years, the building sector alone will add at least 230 billion cubic meters of floor area, imposing a 50% increase in energy demand, if no environmentally responsible measures are employed [1]. With the production of cement contributing about 5 to 9% of the global atmospheric carbon dioxide, cement-based construction is tagged as an environmentally irresponsible endeavor, yet a key for (re)development of the built environment [8, 9]. Although different measures allowed reaching inexpensive per-metric-ton production of concrete and other cement-based materials, accounts of energy consumption and carbon emission still call for employment of more environmentally sustainable and/or green approaches in the industry [10, 11]. Even with the growing concerns on climate change, renewable energy infrastructure like wind and solar farms would still require substantial quantities of concrete for their construction, in addition to the projected rise in sea levels that is expected to trigger massive construction of shore protective walls. With such demand trends, there seems to be no absolute substitute of concrete in meeting modern society infrastructure needs of today and the foreseeable future [12]. Heeding to the call of environmental responsibility, the construction industry is directing significant effort towards incorporating environmental responsibility into lifecycles of cement-based infrastructure, through available green windows including: Carbon Capture and Storage/Utilization (CCS/CCU), Design for Dematerialization (DfD), use of industrial or natural additives for concrete performance enhancement, and full or partial replacement of constituents of cement and cement-based materials with bioavailable/green materials and other industry by-products [13]. However, the production of chemical admixtures to enhance concrete performance is still energy and environmentally taxing. The construction industry must increase energy efficiency and minimize the environmental tax by adopting alternative raw materials and process designs [14, 15]. A recent study reported a possible incorporation of recycled aggregates from construction demolitions as a replacement of up to 100% of coarse aggregates in production of concrete, without significantly impairing the structural performance of reinforced concrete members [16]. In another study, it was demonstrated that municipal solid waste bottom ash could possibly be used as partial replacement for cement in production of concrete [17]. Plant-derived additives have recently provided multiple property enhancement in sustainable concrete production. Their interaction with concrete takes place at the paste matrix level, due to the chemistry of bio-available components in such extracts, but their effects are felt at the gross concrete level [18]. Hazarika et al. [19] reported an increase in compressive strength and improvement in the rate of hydration of concrete mixes prepared with an extract from Okra, a naturally occurring inexpensive biopolymer. In their study, strength deterioration of concrete mixes modified with okra extract and cured in $MgSO_4$-NaCl solution, was found to be lower in comparison to control mixes, depicting better performance under chemical attack [19]. Mahmood et al. [20] showed that a combined dosage of grape (0.25%) and mulberry (0.35%) extracts improved the microstructure of concrete and enhanced its 28th day compressive strength by up to 21% as compared to 15% improvement attained by using a regular chemical water reducing admixture. The extracts also acted as set retarders and improved slumps by up to 200% [20].

Following the importance of finding ways to reduce the reliance on Portland cement and chemical additives in reducing cost and environmental and resource challenges, the work reported in this paper studied the effect of dosing Normal Strength Concrete (NSC) with mucilage extracted from *Opuntia ficus-indica* on the performance of the mix, cost, and environmental impact relative to conventional mixes.

2. BACKGROUND AND OBJECTIVES

As the rest of the world investigates attempts to arrive at various combinations of factors to optimize the construction cost function, rural communities in the Karamoja sub-region in North-Eastern Uganda have in the recent past experienced a considerable level of comfort in mud and wattle residential homes, constructed at costs suiting their low-income levels as shown in Figure 1. These communities have recently adopted the use of mucilage from *opuntia ficus-indica* as a means to elongate maintenance cycles of clay muds that are regularly washed off by striking rains. This local technology has no defined criteria of proportioning the mucilage and the mixing water, but the builders have over the time mastered the desired level of stickiness (viscosity) of the water-mucilage mix, and the consistency/homogeneity of the mud material, as judged by their accumulated experience and their sense of sight and touch. Two main modes of mudding using opuntia mucilage have evolved; one where the whole mass of mud is mixed using the mucilage-water composite, and another where the mudding is carried out with ordinary water and the external surface is then rendered after 24 to 48 hrs using a mixture of clay and sand prepared with water with added mucilage. The study reported in this paper stands as the only documentation of this mode of construction in the context of Uganda.

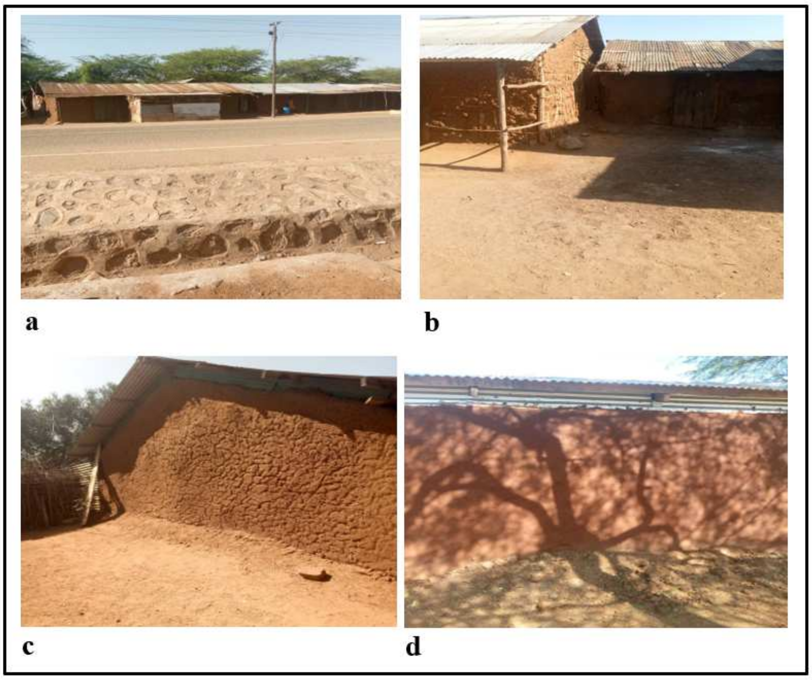


Figure 1 Mud walls
a and b: Mud and wattle construction in North-Eastern Uganda, c: Conventional mud wall after 3 months, and d: Ofim-modified wall after 3 months

In a study by Shanmugavel et al. [3], *Ofim* was dosed into concrete by up to 10%, and a progressive performance enhancement of mucilage-modified mixes was reported with increasing dosages, relative to a control mix. A 10% dosage enhanced the concrete slump by 46% and the 56-day compressive strength by 25.4 %. Another study by Martinez-Molina et al. [21] linked the use of mucilage from *Ofi* to restoration of ancient buildings in Mexico when incorporated in repair mortars. Martinez-Molina et al. [21] studied durability enhancement of mucilage modified mortars dosed with up to 95% by mass replacement of mixing water, and reported positive outcome of the exploration, with the trend of performance enhancement stagnating at mixing-water replacement percentages above 42 %. Mucilage from *Ofi* is also suggested among high molecular weight water-soluble natural polymers with viscosity enhancing properties that could possibly be used as a remedy against constituent segregation in overly plasticized concrete mixes [18].

Recent studies in the literature still lack a thorough analysis of the performance and durability enhancement of conventional concretes and mortars dosed with extracts from *Opuntia ficus-indica*. On the basis of (a) case studies that showed performance enhancement of concrete dosed incrementally up to 10% with *Ofim* [3], (b) the stagnation of performance enhancement at mixing water replacements above 42% [21], and (c) the possible use of *Ofim* as a Viscosity Enhancing Additive (VEA) in highly plasticized concretes [18], the study reported in this paper aimed to provide an in-depth analysis of the improvement in the strength and durability of concrete dosed with *Ofim*, in addition to a micro-structural analysis and an environmental lifecycle assessment to quantify how the usage of *Ofim* leads to decreasing the GHG emissions and embodied carbon in concrete, thus contributing to climate change mitigation.

The main objectives of this study included: (a) determining the approximate *Ofim* mixing-water replacement percentages to achieve optimum mechanical strength and durability performance of NSC, (b) comparing the slump enhancement as reported in similar studies to action of a synthetic concrete plasticizer (SIKA), (c) evaluating the effect of the interaction of *Ofim* and the synthetic admixture (SIKA) on concrete performance, and (d) conducting a comparative environmental impact evaluation between the optimum performance *Ofim*-modified mix and conventional concrete. The novelty of the reported research is that there is no reported research in the literature which address the last three objectives (b, c, and d).

3. EXPERIMENTAL PROGRAM

3.1 Materials

The cement used in the study was Type 1 cement provided by Holcim, a leading cement company in Lebanon, and satisfying European norms (CEM II/A-L) and the Lebanese standards (LIBNOR) [22]. Natural sand, mined from a local site in Lebanon, was used in the study. This was prepacked sand with sharp and angular grains ranging in size between 75 µm and 4.5 mm. The concrete mix design incorporated crushed coarse and intermediate aggregates procured from local suppliers in Lebanon. Physical properties of conventional materials used are summarized in Table 1.

Table 1 Properties of concrete constituent materials used in the study

M	Particle size (mm)	Specific gravity
C	-	3.15
S	0.075 – 4.5	2.59
C	12 - 19	2.68
I	6 - 10	2.68

Sikament®-163, a water reducing admixture produced by the Sika group, was used as a synthetic concrete additive and is referred to as SIKA throughout the paper. The manufacturer specifies the additive as a general use highly effective water-reducer, complying with ASTM C-494 Type A [23] and BS 5075 Part 3 [24]. It is important to note that the use of Sikament®-163 was aimed at increasing slump and was not intended to reduce mixing water and/or increase concrete performance parameters. The manufacturer-declared physicochemical properties of the additive and other information are summarized in Table 2.

Table 2 Properties of Sikament®-163 (SIKA) plasticizer used in the study

Property/Information	Value/Description
Base type	Synthetic type dispersant
Colour	Brown
Density	1.200 kg/l
Total Chloride ion	< 0.1% w/w

Dosage	0.6 – 2.5% (by weight of cement)

Mucilage from *Opuntia ficus-indica* was extracted by water immersion and sieve squeezing. The harvested cladodes were de-thorned by scraping off visible spikes and any surface irregularities and sliced into approximately cuboidal shapes of 5mm maximum thickness (Figure 2a & 2b). The sliced cladodes were soaked in a known mass of tap water in the ratio of 1:2 (cladode slices to water by mass) and stirred gently, covered in an air-tight container, and were left still for at least 48 hrs after which the composite was gently stirred and rammed (Figure 2c). Using sieve No. 200, the composite was filtered to collect the cladodes extract which was referred to as *Ofim* (Figure 2d). The physicochemical properties of *Ofim* extract were determined and are reported in Table 3.

Table 3 Physico-chemical properties of *Ofim* determined on a wet-basis

Category	Property	Quantity	Standard/Method
Physical	Ash in solids	0.29 (%)	Furnace/gravimetry
	Density	1.017 (Kg/L)	Absolute mass
Metals	Chlorides	856 (mg/L)	Titration Hach 8225 [25]
	Potassium	976 (mg/L)	EPA 200-7/8 M [26]
	Sodium	24.2 (mg/L)	EPA 200-7/8 M [26]
Organic	Fat	0.1 (%)	AOAC 963.15 [27] (Modified)
	Carbohydrates	0.25 (%)	Calculation
	Proteins	0.06 (%)	ASTM E1019 M [28]

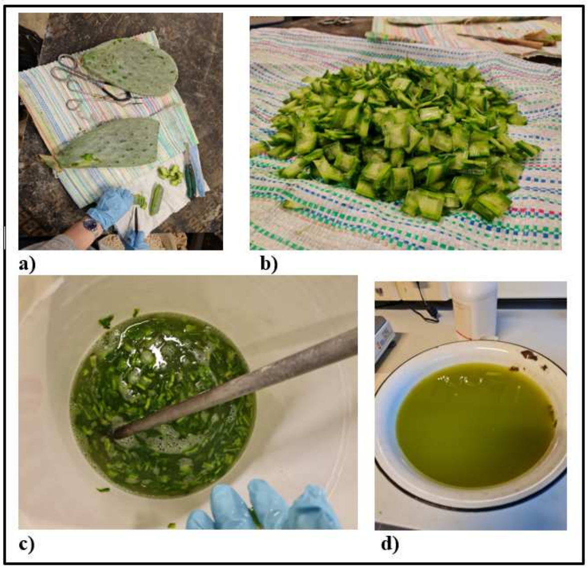


Figure 2 Extraction of *Ofim*

a and b: Slicing of Ofim cladodes, c: Soaking and stirring, and d: Ofim ready for dosage into mixing water

3.2 Mix Design

The concrete mix design was performed in accordance with the ACI 211.1-91 [29], with the conventional/control mix intended to achieve a mean compressive strength of 28 MPa after 28 days of moist curing. The conventional mix was designed for 0.58 fluid/cement ratio, 75 to 100 mm slump, 19 mm maximum aggregate size of 1650 kg/m^3 Dry Rodded Unit Weight (DRUW), 320 kg/m^3 minimum cement content, and 23.5 kN/m^3 initial concrete unit weight. All aggregates were oven dried at 105 °C for 24 hours and air-cooled at room temperature before batching and mixing. The composition of the control mix is summarized in Table 4.

Table 4 Composition of one cubic meter of the control mix

Material	**Batching weight per cubic meter of Concrete (Kg)**	**Proportion of total aggregates (%)**
Cement	360	-
Sand	625	35
Intermediate Aggregates (6 – 10 mm)	446	25
Coarse Aggregates (12 – 19 mm)	714	40
Water	209	-

3.3 Mix Variables

A total of six concrete mixes, identified in Table 5, were prepared for experimental testing. In the first experimental phase, the mixes were tested for slump, compressive strength, split tensile strength, standard flexural strength, static Young's modulus of elasticity, and rate of water absorption. In the second phase, four selected mixes were evaluated for durability performance through determining the freeze-thaw resistance and thermal conductivity.

The mixing time for all mixes was maintained at 3 minutes, with both SIKA admixture and *Ofim* added 1 minute after beginning of the batching procedure. In the mix dosed with SIKA and *Ofim*, *Ofim* was added and immediately followed by SIKA. Part of the mixing water, not less than 10 times the quantity of SIKA, was deducted and used to dilute the SIKA prior to addition into the concrete mixer. Each mix was conducted at least twice, and average values of the two mix regimes are presented for all tested parameters.

The dosage of SIKA chemical plasticizer followed a recommendation by the manufacturer to conduct trial mixes to ultimately define suitable dosages for specific intended applications of concrete, while the dosage of the *Ofim* followed an attempt to obtain comparable concrete slumps within the slump-envelope of the SIKA chemical additive. Strength tests were conducted at standard time intervals up to 56 days, while freeze-thaw resistance and thermal conductivity testing were conducted at the age of 28 days. Moist curing was conducted for all test specimens up till the day of testing.

Table 5 Mix designations used in the study

Mix	**Mix Designation**	**SIKA Dosage** **(% by cement mass)**	**Mixing-water mass-replacement (%)**	**Mix Description**
1	Control	-	-	Control mix prepared without chemical or bio-additive modification.
2	*Ofim*-15	-	15	*Ofim* bio-additive-modified mix with 15% mass replacement of mixing water
3	*Ofim*-25	-	25	*Ofim* bio-additive-modified mix with 25% mass replacement of mixing water
4	*Ofim*-50	-	50	*Ofim* bio-additive-modified mix with 50% mass replacement of mixing water
5	SIKA-1.5	1.5	-	SIKA-plasticized mix with intermediate manufacturer-recommended dosage of 1.5% by mass of cement
6	*Ofim*-15 + SIKA-1.5	1.5	15	15% water mass replacement with *Ofim* bio-additive and 1.5% SIKA-dosed mix

3.4 Test Methods

The slump test was conducted on fresh concrete to evaluate the effect of *Ofim* on concrete consistency in comparison with SIKA, in accordance with the ASTM C143 [30]. Strength tests were conducted at standard time intervals including after 7 (only for compressive strength), 28, and 56 days; three standard specimens were tested for each strength parameter. The compression test was conducted on Ø100 × 200 mm cylinders, prepared and loaded at a standard rate of 0.25MPa/s under an automatic universal testing machine, in accordance with the ASTM C39 [31]. To determine the splitting tensile strength, a diametrical compressive force was applied on Ø100 × 200 mm cylindrical specimens at a standard loading rate specified in ASTM C496 [32], under an automatic UTM. The mode of loading exerted on the specimen was intended to cause triaxial compression and thus induce tensile failure, resulting into an indirect tensile strength test. The mean stress to strain ratio of three hardened Ø150×300 mm cylindrical concrete specimens at the specified curing age was determined for each mix, and reported as the Young's modulus, in accordance with the ASTM C469 [33]. The flexural strength test was conducted on standard, simply supported beams with center-point loading. Beams of 100 × 100 × 350 mm were used in this method and loaded as specified in the ASTM C293 [34]. The average maximum failure resistance of standard specimens from each mix was reported as the modulus of rupture (MOR).

Durability properties were determined after 28-days of moist curing of the test specimens. For the rate of water absorption, time-dependent water ingress into unsaturated concrete exposed to water only on one surface was measured. The method of specimen preparation, conditioning, and testing was as specified in ASTM C1585 [35]. $\text{Ø}100 \times 50\ \mathrm{mm}$ cylindrical specimens were coated with epoxy on all unexposed sides and one side parallel to the diameter was submerged in tap water for nine days. Steady-state thermal conduction through concrete slab specimens of dimensions $300 \times 300 \times 40\ \mathrm{mm}$ was evaluated using a standard heat flow meter apparatus, in accordance with ASTM C518 [36] to obtain the thermal conductivity of studied mixes. Resistance to freezing and thawing of concrete specimens was determined by measuring the loss in Relative Dynamic Modulus of Elasticity (RDME) of standard molded specimens under rapid freezing and thawing in accordance with ASTM C666 [37]. For each of the four mixes, two prismatic specimens of size $75 \times 100 \times 400\ \mathrm{mm}$ were molded and cured for 28 days before exposure to freeze-thaw cycles in a standard chamber. Each complete freeze-thaw cycle involved a temperature drop from $4^{0}\mathrm{C}$ to $-18^{0}\mathrm{C}$, and a subsequent rise from $-18^{0}\mathrm{C}$ to $4^{0}\mathrm{C}$, and lasted 4 hours and 40 minutes, resulting in a total of 36 complete cycles in one week.

4. TEST RESULTS AND ANALYSIS

4.1 Slump

The effect of *Ofim* on the workability of concrete was insignificant, even at high water mass replacements. It is important to note that an enhancement of 19.4% in the concrete slump was registered when concrete was simultaneously dosed with SIKA-1.5 and *Ofim*-15 water mass-replacement, as compared to concrete dosage with only SIKA-1.5. Figure 3 shows the slumps of *Ofim*-modified mixes as compared to slumps attained at different SIKA dosages.

The low slumps in *Ofim*-modified mixes despite the gelling action of *Ofim* can be explained by the physical absorption of water by polysaccharides present in *Ofim* due to hydrogen bonding during mixing, thus an increase in viscosity of the *Ofim*-modified mixes [38]. It was also evident that as mixing continued during shearing for the mixing-time duration, the viscosity of the mixer content increased with time, as the bonds reaggregated rapidly to restore the mixes to near control viscosity/slumps. This phenomenon was reported in the study of the rheology of cement pastes containing polysaccharide gums [38].

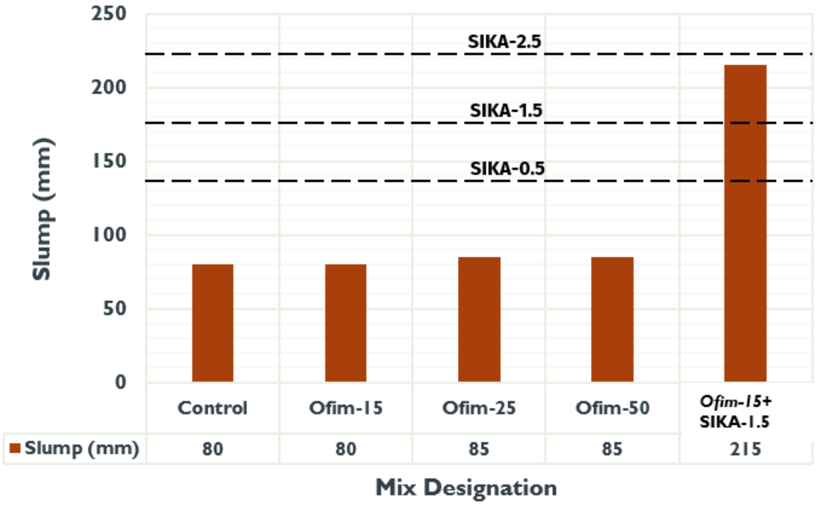


Figure 3 Slump values of fresh concrete mixes (dashed lines present the concrete slump of mixes with different SIKA dosages)

4.2 Micro-characterization

4.2.1 Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) images of the modified and non-modified concrete mixes were acquired at the 56th day after casting and used to determine the effect of *Ofim* and SIKA additives on the concrete microstructure. SEM analysis of images is dependent on visual features of micro-samples, observable in the Backscatter image extracts, including particle rearrangement and entanglement, and difference in gray levels. Deposits of hydration products can semi-qualitatively be identified in such images by differentiating levels of gray shades: light gray irregular shape areas show calcium hydroxide crystals $Ca(OH)_2$, dark gray areas represent calcium silicate hydrate (C-S-H), and black areas indicate micro pores and cracks [39]. Mass deposit of Calcium Silicate Hydrate (C-S-H), with isolated and loosely attached crystals of $Ca(OH)_2$ on the hydrated composite, was observed in the microstructure of the control mix specimen (Figure 4a). In all *Ofim*-modified mixes (Figure 4b, 4c, 4d), an even distribution of $Ca(OH)_2$ and (C-S-H) was visible, with reordered microstructures into entangled crystallites. In the mix simultaneously dosed with SIKA and water mass-replacement of *Ofim*, colorless ettringite crystals were visible. It is normal that in about 3 days of concrete casting, most of the ettringite is transformed into monosulfoaluminate, and ettringite only remains stable even up to a period of 1 year in concrete with pozzolanic activity [39-41]. Strips of ettringite, visible in backscatter images at 56-days, depict a mild-quasi pozzolanic activity in the SIKA-1.5+ *Ofim*-15 mix (Figure 5). This could be attributed to further interaction of *Ofim* with $Ca(OH)_2$ producing other calcium complexes [21].

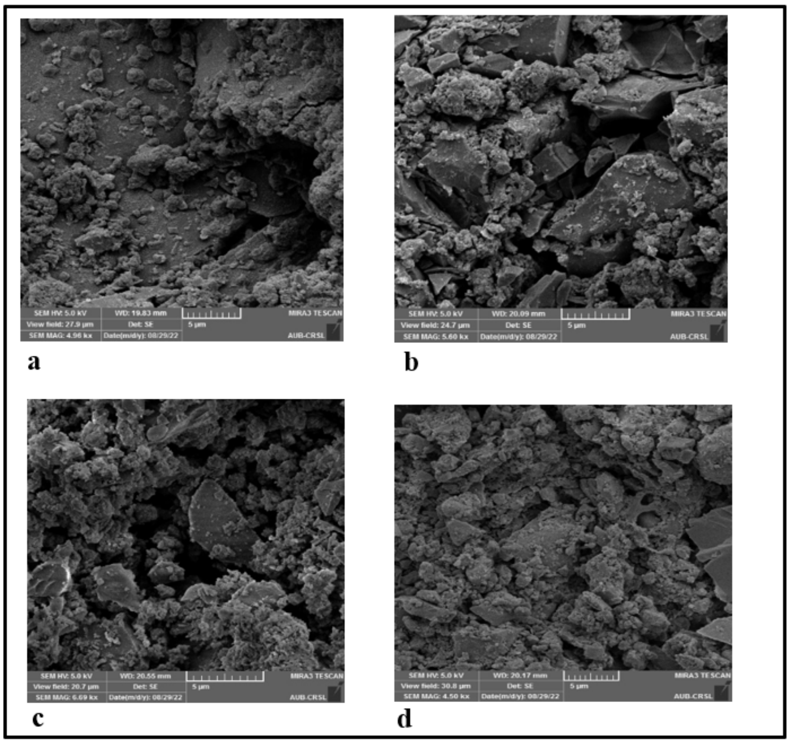


Figure 4 SEM Backscatter images of concrete samples
a: Control mix, b: Ofim-15, c: Ofim-25, d: Ofim-50

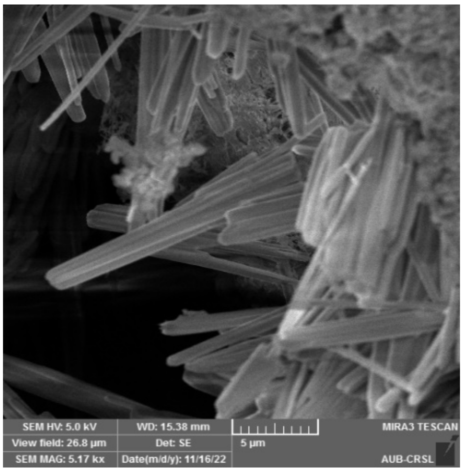


Figure 5 SEM Backscatter image of *Ofim*-15 + SIKA-1.5 showing ettringite rods at 56 days

4.2.2 Fourier Transform-Infrared spectroscopy (FTIR)

The interaction of *Ofim* bio-admixture with cement particles during hydration was investigated using FTIR spectroscopy. For this aim, IR spectra of *Ofim*-modified mixes were acquired and compared to the spectrum of the control mix. FTIR spectra (Figure 6) indicated complex interaction of the mucilage and cement. The broad peak with minimum at 3466 cm^{-1} corresponds to OH stretching of carboxylic groups, and OH groups of polysaccharides. The hydrophilic character of the OH group allows moisture to bind to the *Ofim* biopolymer components contributing to moisture retention and hydration regulation in *Ofim*-modified mixes. The peaks observed at 2851 cm^{-1} and 2926 cm^{-1}, correspond respectively to the symmetric and asymmetric stretching modes of methylene (CH_2) group in *Ofim* polysaccharides, and are apparent in *Ofim*-15 and *Ofim*-50 concrete mixes. Furthermore, in those mixes, the band near 1799 cm^{-1} corresponds to the stretching of the carbonyl group (C=O) of galacturonic acid of pectin, a heteropolysaccharide commonly found in several types of plant-based biopolymers, and of free carboxylic acid groups of galacturonic acid in the bio-admixture.

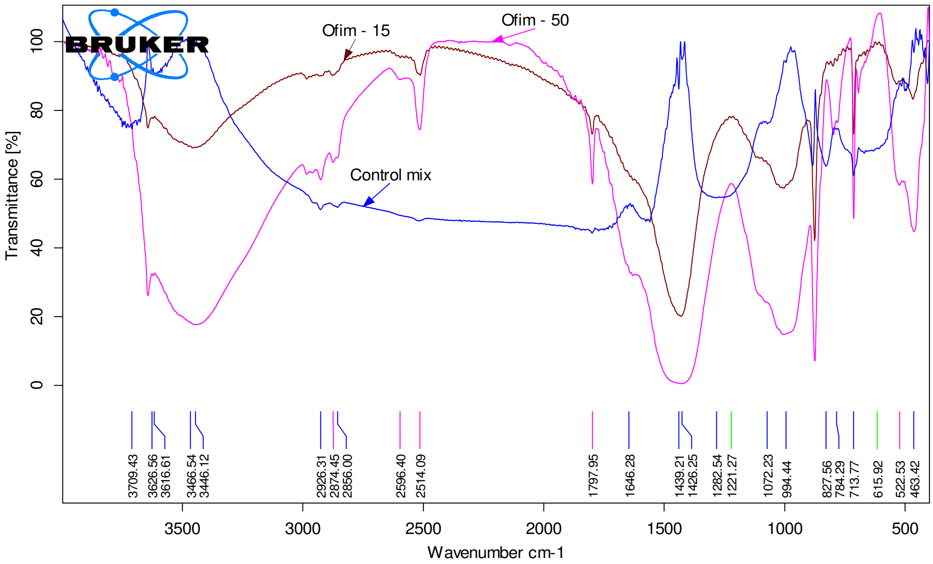


Figure 6 FT-IR spectra of selected concrete mixes

The broad band in the 1300–1700 cm^{-1} region in *Ofim*-15 and *Ofim*-50 modified concrete, with two absorptions minimum near 1646 cm^{-1} and 1426 cm^{-1}, is associated with carboxylate ion present in galacturonic acid of pectin and amides present in protein. The intense bands near 1100, 994 and 883 cm^{-1} of the 850–1200 cm^{-1} region indicate C-O-C vibrations of glycosidic bonds and C-C vibrations of pyranoid rings of pectin.

The FTIR results support the chemical analysis of the composition of *Ofim* bio-admixture and suggest the presence of both pectins and proteins as the major chemical constituents in *Ofim* bio-admixture. Polysaccharides help in retaining the moisture content in cement, and the hydrophilic parts of proteins attach to water molecules through hydrogen bonds, which keeps the cement paste moisturized [3]. Thus, proteins and polysaccharides contribute to retarding the drying shrinkage of the modified cement preventing the formation of cracks [3]. Furthermore, the interaction of Ca^{2+} ions with the chemical constituents of *Ofim*, mainly the acidic component of bio-admixture such as galacturonic acid group, results in strong intermolecular association between the galacturonan chains by forming calcium bridges. This also increases the overall viscosity of the mix [19], and explains the overall even distribution of $Ca(OH)_2$ and (C-S-H) into entangled crystallites as observed at the microstructure level.

4.3 Mechanical Properties

Compressive strength, splitting tensile strength, static modulus of elasticity, and standard flexural strength were tested in conformance to respective ASTM standards as mechanical strength parameters of the studied mixes. The effect of *Ofim* water-replacement was found to be more significant at 56 days of testing.

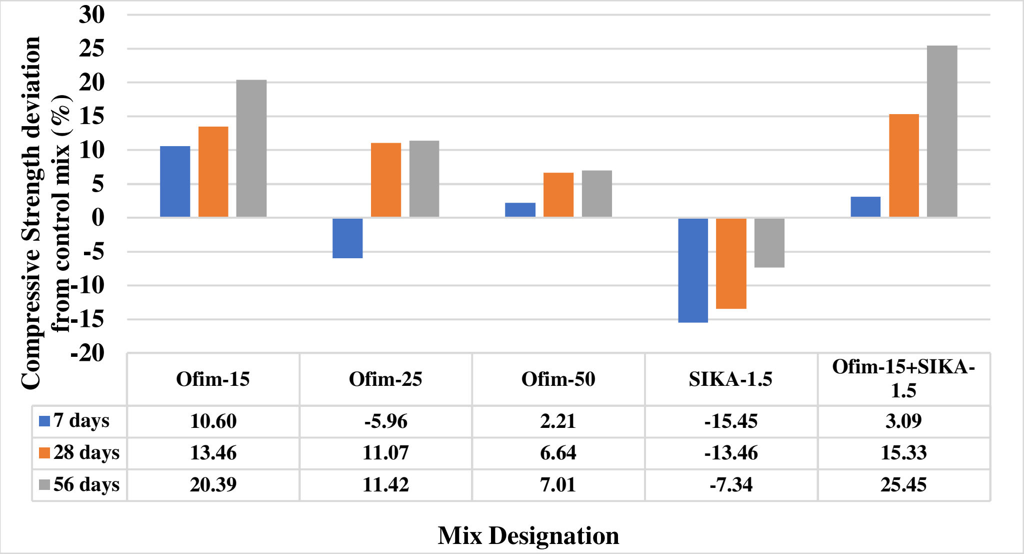
4.3.1 Compressive strength

The compressive strength of the different mixes was measured at defined time intervals of moist curing and the results are presented in Table 6. While no significant effect of *Ofim* water mass replacement was observed on the slump of concrete, *an* enhancement of the compressive strength was observed in *Ofim*-modified concrete mixes relative to the control mix. Namely, the 56-day compressive strength increased by +20.4%, +11.4% and +7% for the 15%, 25% and 50% *Ofim* water mass replacements, respectively. However, *Ofim*15+SIKA1.5 enhanced concrete compressive strength by +25.4%. Figure 7 presents compressive strength values of all mixes relative to the control mix.

Enhancement of strength performance of *Ofim*-modified concrete mixes can be attributed to the effect of polysaccharides present, which facilitate the action of *Ofim* as an adhesive that produces a solid microstructure as observed in the SEM backscatter images obtained from 56-day cured micro samples and discussed in the micro-characterization section [3]. *Ofim* facilitated reordering of the hydrated composite into a well-packed homogeneous microstructure with even distribution of hydration products. The reordering is attributed to the consumption of Ca^{2+} by the *Ofim* pectin in the formation of calcium bridges during hydration [3]. With the longer initial setting times of *Ofim*-modified cement pastes, it is evident that *Ofim* acts as a set retarder which also facilitates gradual and even strength generation, preventing flash setting and Delayed Ettringite Formation (DET) [3]. The retarding effect could be as a result of the thickening of the diffusion coating on C_3A grains for all polysaccharide-modified suspensions, thus elongation of the dormant zone [42]. The reduction in compressive strength with increase in water mass replacement percentage from 15% to 50% could be attributed to the rate of strength generation. At higher percentages of water mass replacement, a 56-day period may not be adequate to achieve the maximum compressive strength, which would be much higher for longer duration of curing. This is consistent with the findings of Martinez-Molina, et al. in which the strength of mortar mixes dosed with *Ofim* at higher water mass replacements notably increased up to a period of 2,145 days of moist curing [21].

Mix Designation	**Compressive strength (MPa)**			**Splitting Tensile Strength (MPa)**		**Modulus of Rupture (MOR) (MPa)**		**Young's Modulus (MPa)**
	7-days	***28-days***	***56-days***	***28-days***	***56-days***	***28-days***	***56-days***	***28-days***
Control	22.7	29.4	30.7	2.8	2.9	4.9	6.1	27895
Ofim-15	25.1	33.3	36.9	3.0	3.1	5.0	5.8	27027
Ofim-25	21.3	32.6	34.2	2.8	3.2	4.2	5.4	27782
Ofim-50	23.2	32.3	32.8	2.5	3.0	4.1	5.3	27971
SIKA-1.5	19.2	25.4	28.4	2.5	3.2	5.3	5.7	28442
Ofim-15+ SIKA-1.5	23.4	33.9	38.5	2.6	2.9	6.1	6.2	30291

Table 6 Test results of the hardened-state mechanical properties



	Ofim-15	**Ofim-25**	**Ofim-50**	**SIKA-1.5**	**Ofim-15+SIKA-1.5**
■ 7 days	**10.60**	**-5.96**	**2.21**	**-15.45**	**3.09**
■ 28 days	**13.46**	**11.07**	**6.64**	**-13.46**	**15.33**
■ 56 days	**20.39**	**11.42**	**7.01**	**-7.34**	**25.45**

Figure 7 Percentage deviation of compressive strength values relative to the control mix

4.3.2 Splitting Tensile Strength

Values of the splitting tensile strength are presented in Table 6. Both SIKA dosage and *Ofim* water mass replacements enhanced the splitting tensile strength relative to the control mix. The 56-day split tensile strength was enhanced, relative to the control mix by +8.8%, +10.5% and +3.5% for the 15%, 25% and 50% water replacements, respectively. There was no effect of an interaction of *Ofim* and SIKA on the split tensile strength. Figure 8 presents the percentage change in the tensile splitting strength of each mix relative to the control mix.

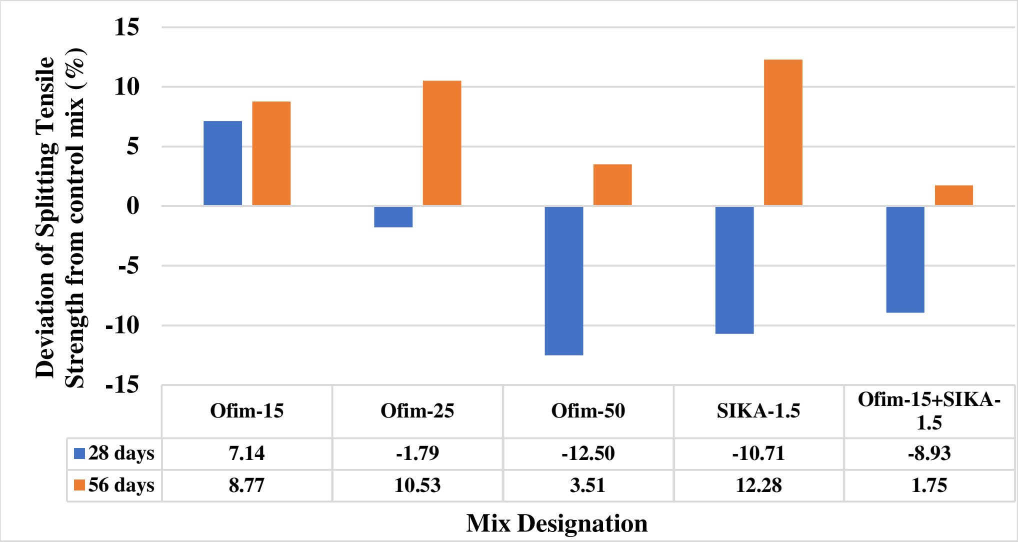


Figure 8 Percentage deviation of splitting tensile strength values relative to the control mix

4.3.3 Young's Modulus of Elasticity

The modulus of elasticity of each mix was computed at working stress up to 40% of the predetermined ultimate concrete compressive strength and results are presented in Table 6. There was no significant effect of *Ofim* and SIKA on the Static Modulus of Elasticity measured at 28 days, however, the values increased with an increase in *Ofim* water-replacement percentage as shown in Figure 9

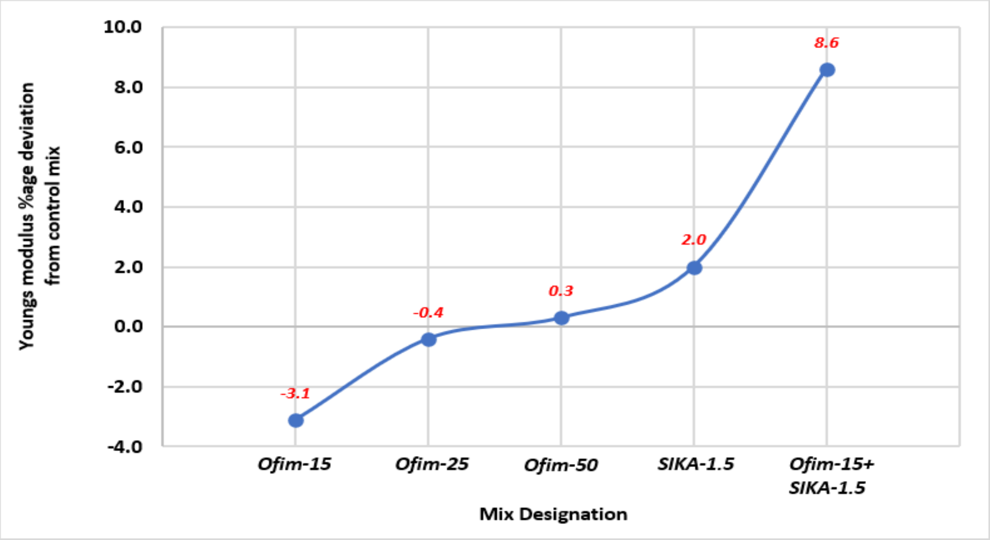
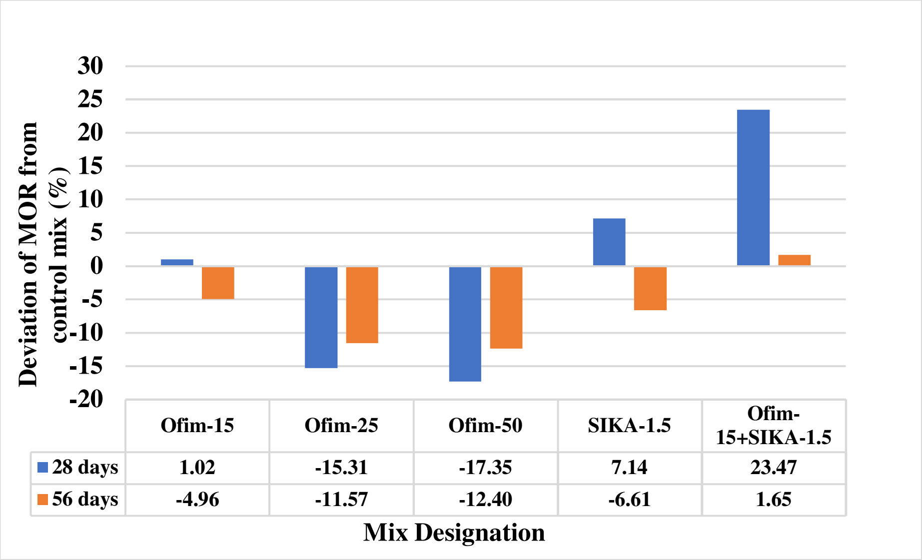


Figure 9 Percentage deviation of Young's modulus values relative to the control mix

4.3.4 Standard Flexural Strength

In reference to Table 6, there was a reduction in the 56-day standard flexural strength, relative to the control mix, by 5.0%, 11.6% and 12.4% for the 15%, 25% and 50% *Ofim* water mass replacements, respectively. The effect of interaction of *Ofim* and SIKA on concrete standard flexural strength was noticeable at 28 days but insignificant at 56 days as presented in Figure 10. The load deflection curves of four mixes were plotted to establish the energy dissipation of additive-modified mixes compared to the control mix (refer to Figure 11). The load-deflection are almost identical, indicating no significant effect of the additives on the flexural load-deflection behavior. The fracture energy was computed as the area under the load-deflection curve up to 0.5Pmax after ultimate deflection. Ofim-modified concrete mixes dissipate almost 90% of the fracture energy of the control mix. Ductility indices in Table 7 are the ratios of fracture energy of the modified mixes relative to the control mix.



	Ofim-15	Ofim-25	Ofim-50	SIKA-1.5	Ofim-15+SIKA-1.5
■ 28 days	1.02	-15.31	-17.35	7.14	23.47
■ 56 days	-4.96	-11.57	-12.40	-6.61	1.65

Figure 10 Percentage deviation of standard flexural strength values relative to the control mix

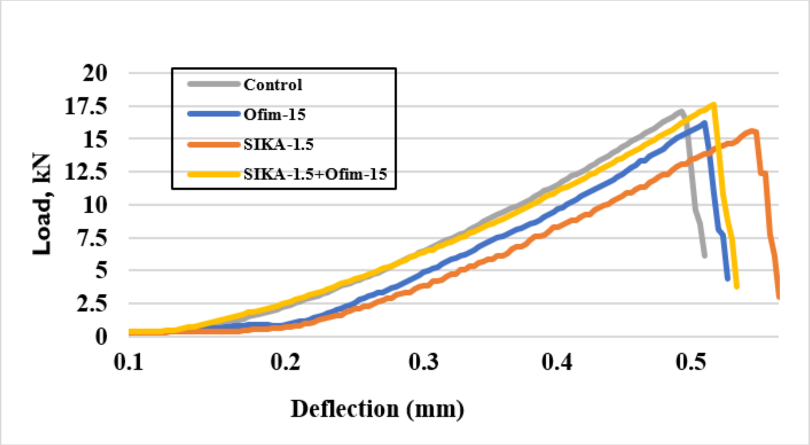


Figure 11 Flexural load versus deflection curves of four selected mixes

Table 7 Fracture energy of four selected mixes

Mix Designation	Fracture Energy (kN-mm)	Ductility Index (µ)
Control	3.164	-
Ofim-15	2.852	0.90
SIKA-1.5	2.762	0.87
Ofim-15 + SIKA-1.5	2.891	0.91

4.4 Durability Properties

Based on results of the hardened mechanical strength properties, three durability tests were conducted on four selected mixes after 28 days of moist curing of standard specimens: rate of water absorption, thermal conductivity, and freeze-thaw resistance. The chosen mixes are: Control, *Ofim*-15, Sika-1.5, and *Ofim*-15+Sika-1.5.

4.4.1 Rate of water absorption

As shown in Figure 12, the rate of water absorption/ingress was reduced, relative to the control mix, by 14.7%, 38.7% and 25.3% for the 15%, 25% and 50% *Ofim* water mass replacement, respectively. A reduction of 36.0% relative to the control mix, was recorded for the 1.5% SIKA dosage mix.

The reduction in water ingress in mucilage-modified mixes is attributed to the reordering of hydrated grains forming a solid microstructure, as observed in the SEM backscatter images. Grain entanglement facilitated by the physical gelling action of *Ofim*, especially pronounced in the SEM backscatter images of the *Ofim*-25 and *Ofim*-50 concrete mixes (Figures 4c and 4d), could be responsible for expelling possible large micropores and ridges during mixing.

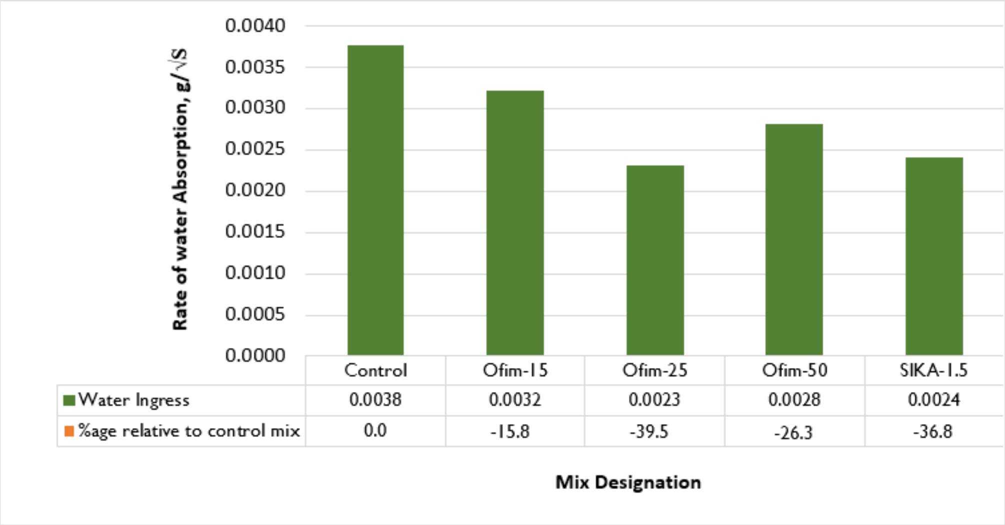


Figure 12 Secondary rate of water absorption of concrete disc specimens

4.4.2 Thermal conductivity

The thermal conductivity (K-value) of the *Ofim*-15 mix was lower than that of the control mix by 13.9% while the mixture with a combination of *Ofim* and SIKA exhibited a K-value lower than the control mix by 9%. There was no notable effect of SIKA-1.5 on the thermal conductivity of concrete. K-values of the studied mixes are presented in Figure 13. The reduction of K-value will further reduce energy consumption by reducing ambient temperature fluctuations when deployed in building applications.

Figure 13 Thermal conductivity of concrete mixes

K-values as low as 0.6 W/m/°K are attainable with the use of light-weight aggregates and air entrainment in concrete, thus enhancing heat energy conservation since air is a poor conductor of heat. Studies by Cavalline et al. (2017) [43] and Sun et al. (2017) [44] are consistent with the correlation-causation effect of low K-values and porosity and light weight of concrete. Contrary to the latter studies, *Ofim*-modified concrete mixes exhibited insulating properties, with lower K-values relative to conventional concrete, despite evidence of solid microstructures revealed by the SEM backscatter images. The reduction in K-values could be attributed to the surface adsorption of *Ofim* to the surface of aggregates and cement particles during hydration. This leads to the alteration of aggregates surface properties within the microstructure, affecting the inter-particle heat transfer, which is eventually notable at sample macro level in the heat flow meter test [45].

4.4.3 Freeze-thaw Resistance

The transverse fundamental frequency of concrete samples was tested after every 36 freeze-thaw cycles, up to 180 cycles, from which the Relative Dynamic Modulus of Elasticity (RDME) of each mix was computed (refer to Table 8). The rate of loss of RDME in each mix was considered the measure of resistance to rapid freezing and thawing.

$$P_c = \left(\frac{{n_1}^2}{n^2}\right) \times 100$$

Where:
$P_c =$ RMDE after c freeze-thaw cycles, %
$n_1 =$ mean fundamental transverse frequency after c cycles, Hz

n = mean pre-exposure fundamental transverse frequency, Hz

Table 8 RDME of prismatic specimens after every 36 freeze-thaw cycles.

Mix Designation	**Relative Dynamic Modulus of Elasticity Pc (%); Recorded after every 36 cycles**					
	0	**36**	**72**	**108**	**144**	**180**
Control	100.00	87.59	82.84	71.53	59.12	55.28
***Ofim*-15**	100.00	97.51	90.10	87.74	85.40	83.10
SIKA-1.5	100.00	94.86	80.30	77.96	69.08	64.82
***Ofim*-15+SIKA-1.5**	100.00	95.16	90.39	81.27	64.39	62.44

After exposure to 180 freeze-thaw cycles, the control mix samples had degraded to 55.28% of its initial mean RDME, while for *Ofim*-15 samples still retained 83.10% of the initial mean RDME. SIKA-1.5 and *Ofim*-15 + SIKA-1.5 mixes degraded to 64.82% and 62.44% of their initial RDME values, respectively. This is an indication that deterioration due to the repeated freeze-thaw cycles proceeded much slower in *Ofim*-modified concrete mixes, with an average rate of 3.38% for every 36 cycles, as compared with 8.94%, 7.04% and 7.5% for the control, the SIKA-1.5, and the *Ofim*-15 + SIKA-1.5 mixes. There was no linear relationship between the RDME and the number of cycles in all studied mixes, however after 72 cycles, the plot of the *Ofim*-15 mix displayed a perfect linear relationship with a slope of 0.065 (Figure 14).

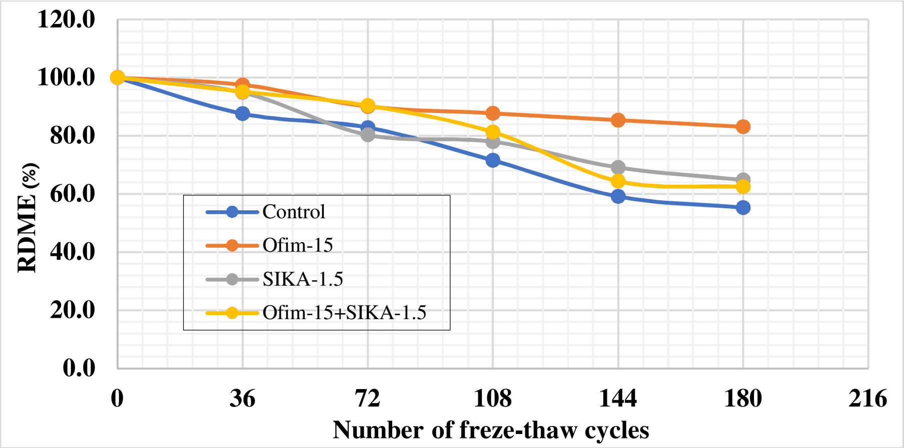


Figure 14 Loss in RDME/rate of deterioration after every 36 freeze-thaw cycles

Air entrainment plays a pivotal role in dissipating hydraulic pressure during freezing and thawing cycles as an effective means of improving freeze-thaw resistance of concrete. However for the same amount of entrained air, sound concrete with solid and a homogeneous microstructure would deteriorate at much lower desirable rates [46]. SEM backscatter images *Ofim*-modified mixes showed modification of hydrated grains of the concrete composite, which could explain its better performance in resisting the effects of freezing and thawing. Homogeneity of the microstructure of the *Ofim*-modified mix helps in resisting cavity dilation and rupture caused by pore pressure during freezing and thawing action, which can be attributed to the undesirably quicker deterioration in other mixes. Regulated setting in the *Ofim*-modified mix aids in preventing microstructural cracking, thus a sound microstructure that could be responsible for resisting disruption of the hydrated paste-aggregates interface, caused by the cumulative effects of freeze-thaw cycles.

4.5 Environmental Lifecycle Assessment

The Life Cycle Assessment (LCA) methodology was employed to evaluate environmental loads of selected concrete mixes in accordance with the ISO Standard 14040 – 14043 [47]. The evaluation involved definition of the goal and scope of the assessment, life cycle inventory formulation, Life Cycle Impact Analysis (LCIA) and results interpretation and conclusions.

4.5.1 Goal and scope

The goal of the evaluation was to compare the environmental impact of conventional concrete to *Ofim*-modified concrete and provide significance to the adoption of *Ofim* in use as a bio-additive in production of sustainable concrete. Only two mixes were considered in the comparative evaluation of environmental impact of concrete production; the control mix and the *Ofim*-15 mix that exhibited the highest compressive strength performance at 56 days. A cradle-to-gate system boundary was considered (Figure 15) since the scope of study was limited to concrete production and assessment of its performance at material level. The study employed OpenLCA, an open-source tool, to model all product flows and processes to achieve its objective, excluding environmental impact from material transportation.

The comparative environmental evaluation between the selected mixes was based on two functional units:

1. 1 cubic meter of concrete produced.
2. 56-day compressive strength of 30 MPa as the performance parameter.

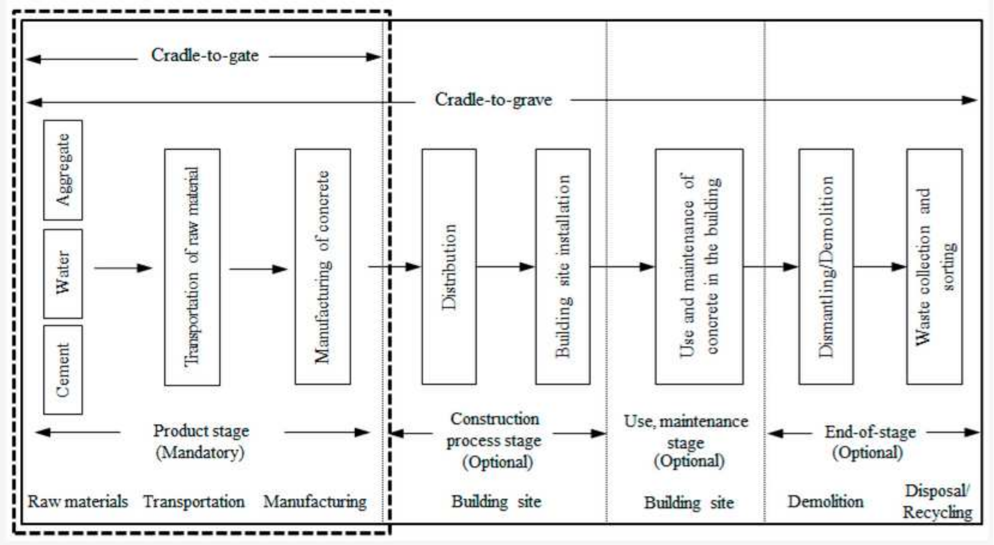


Figure 15 Lifecycle of concrete infrastructure [48]

4.5.2 Lifecycle inventory formulation

After defining the scope and goal, an inventory was created for the life cycle assessment for each mix in the study. Materials required to produce concrete with the selected functional units were computed by leveling the performance functional unit of both mixes to 30 MPa. The Approximate Percentage-point Cement Reduction (APCR) method was adopted to level the performance functional unit. In this method, the initial amount of cement required per cubic meter of *Ofim*-15 concrete mix was gradually reduced until a 56-day compressive strength of 30±2 MPa was attained. Table 9 shows the mixes cast with reduced quantities of cement to level the 56-day compressive strength of *Ofim*-15 to the selected performance functional unit. No leveling was required for the control mix since the performance functional unit was selected based on its 56-day compressive strength.

Table 9 *Ofim-15* compressive strength leveling using the APCR method

Mix	% of cement relative to control mix	Reduced % of cement	56-day Compressive strength (MPa)
Ofim-15	100	0	36.9
Ofim-15/15 [1]	85	15	26.0
Ofim-15/10 [2]	90	10	29.1

[1] *Ofim*-15/15 concrete mix with cement reduced by 15% by weight

[2] *Ofim*-15/10 concrete mix with cement reduced by 10% by weight

Material proportioning for *Ofim*-15/10 with compressive strength in the approximate range of the performance functional unit is presented in Table 10 below.

Table 10 Material proportions for the APCR method inventory analysis

FU	**$1m^3$, 56-day Compressive Strength = 28MPa**			
Material	**Quantity (Kg/m^3 of concrete)**		**Percentage in mix (%)**	
	Control	***Ofim-15/10***	**Control**	***Ofim-15/10***
Cement	360	324	15.3	14.0
Sand	625	625	26.6	27.0
Intermediate Aggregates	446	446	18.9	19.2
Coarse Aggregates	714	714	30.3	30.8
Water	209	177.65	8.9	7.7
Ofim	-	31.35	0.0	1.4
Total	**2354**	**2318**	**100**	**100**
Concrete mixer (Energy requirement)	0.5 KW for 1.18 hrs			

Cactus being considered as a waste product without a service provider, the total mass of the fluid was taken as 209 Kg (*Ofim* + mixing water) for all mixes for purposes of comparative assessment. All raw material and energy input processes are provided by service providers and contained in the ELCD greendelta database utilized in this comparative assessment. Illustrations of unit processes for aggregates (gravel and sand) and cement are shown in Figure 16, showing process inputs and outputs.

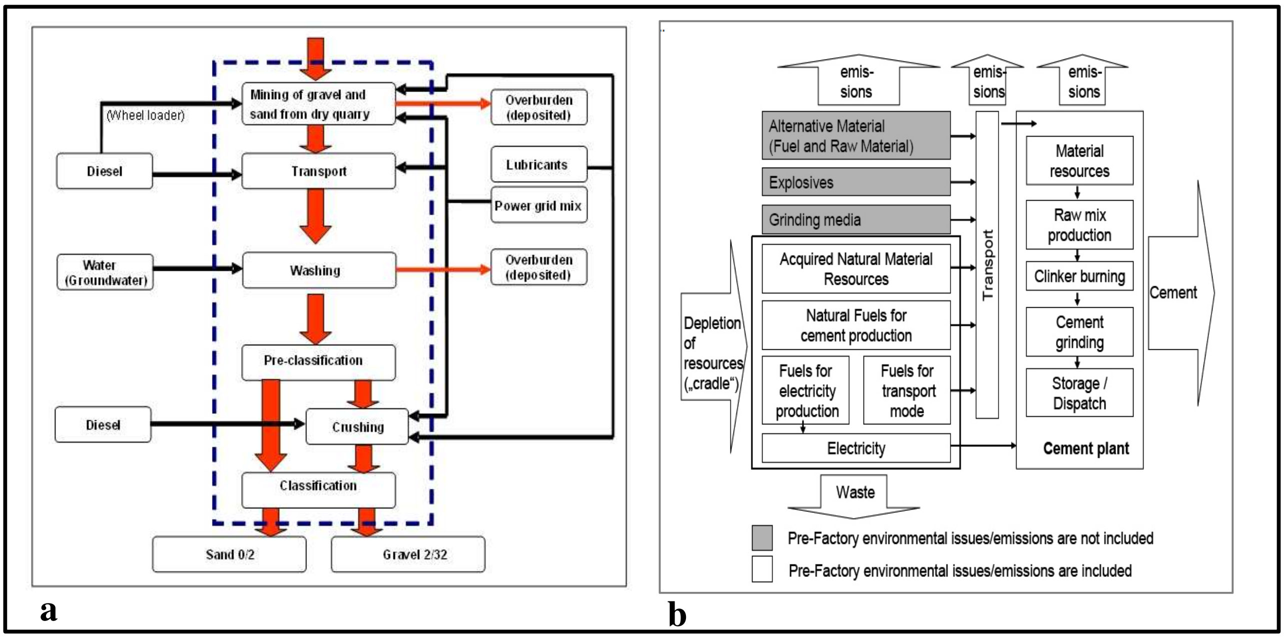


Figure 1 Material flows as modelled in OpenLCA
a: Sand and Gravel, *b*: Cement.
Source: ELCD greendelta database

4.5.3 Comparative Lifecycle Impact analysis

Using the CML (baseline, January 2015) impact assessment method, environmental impacts of the product system of the conventional and the modified *Ofim*-15 were calculated based on nine (9) selected impact categories, and thereafter a comparative analysis was conducted to derive appropriate interpretations and conclusions regarding the environmental significance of adoption of *Ofim* in sustainable concrete production. Table 11 shows results of the LCIA for the conventional concrete and *Ofim*-15.

Relative environmental impact of the two mixes for all impact categories was computed and plotted as in Figure 17. The ralative environmental impact is the ratio of the quantified emission of *Ofim*-15 to the quantified emission of conventional concrete for the same impact category. Relative analysis was employed for simplicity of analysis, such that ratios either greater or less than 1 would distinctly imply greater or lesser impact of *Ofim*-15 over conventional concrete.

For both the adopted methods of performance leveling, the computed relative environmental impact for *Ofim*-15 concrete mix was less than 1 in all considered impact categories, averaging 0.904. This implies a 9.6% average reduction in emissions to the environment when a 15 % water mass replacement with *Ofim* is adopted in concrete production.

Table 11 Lifecycle Impact Analysis results of different project variables

Impact category	**Environmental Impact**		
	Reference unit	**Control**	***Ofim-15***
Climate change - GWP100	kg CO_2 eq.	331.3603615	298.844006
Depletion of abiotic resources - elements, ultimate reserves	kg antimony eq.	5.69484E-06	5.18091E-06
Depletion of abiotic resources - fossil fuels	MJ	1321.625099	1196.63124
Eutrophication - generic	kg PO4--- eq.	0.097577529	0.088264103
Freshwater aquatic ecotoxicity - FAETP inf	kg 1,4-dichlorobenzene eq.	0.090954488	0.082494151
Human toxicity - HTP inf	kg 1,4-dichlorobenzene eq.	9.307197039	8.419828753
Marine aquatic ecotoxicity - MAETP inf	kg 1,4-dichlorobenzene eq.	22391.86051	20336.57338

Ozone layer depletion - ODP steady state	kg CFC-11 eq.	1.6876E-05	1.52928E-05
Photochemical oxidation - high Nox	kg ethylene eq.	0.062815471	0.056810522
Terrestrial ecotoxicity - TETP inf	kg 1,4-dichlorobenzene eq.	0.34211227	0.308449835

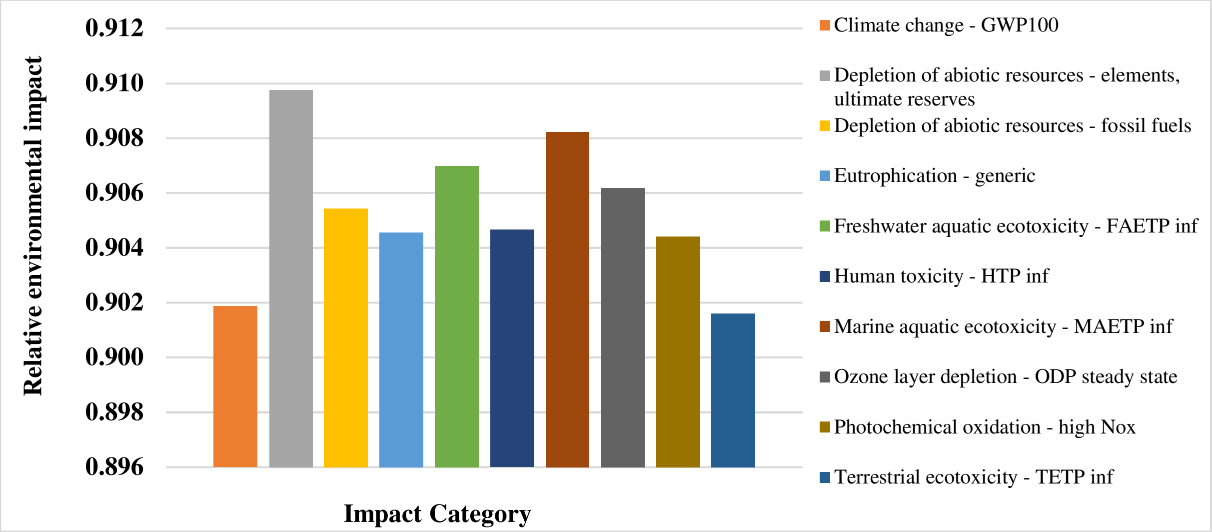


Figure 17 Relative environmental impact of *Ofim-15* to conventional concrete

The notable reduction in the environmental impact of the *Ofim*-15 mix lifecycle can be attributed to the sensitivity of environmental impact of concrete production to the amount of cement used in the process, as the method involved a direct cement reduction [9]. As per IEA (2022), embodied carbon in construction materials contribute to 13% of the global GHG emissions. Thus, a reduction of around 10% (climate change category, Figure 17) is substantial when looking at the scale of use of concrete materials globally.

4.5.4 Environmental Cost Indicator (ECI)

The ECI is a summation of all impact equivalents, computed using a weighting system developed by the Intergovernmental Panel on Climate Change (IPCC). The system derives a cost variable as shown in Table 12, for each impact category as a weight, based on the *shadow price method*, shadow price being the cost level allowable for governments to control each unit of emission (prevention price). The cost weight of each impact category is then multiplied by the equivalent units to obtain an identical unit parameter for all the categories, the ECI [49]. The cumulative impact of conventional concrete and *Ofim*-15 in terms of how much it would cost to restore the damage caused by each emission from 1 m^3 of each mix is presented in Table 12. The strength performance of *Ofim*-15 directly translated into its performance in minimizing environmental impact, thus savings on the ECI of 23 € per cubic meter of conrete. The strength performance of Ofim-15 directly translated into its performance in minimizing environmental impact, thus savings on the ECI of 23 € per cubic meter of conrete.

Table 12 Environmental cost weighting factors for different impact categories [49]

Impact category	**Unit**	**Weighting Factor** (€/ unit)
Global warming	kg CO_2-eq	0,05 €
Ozone depletion	kg CFC-11-eq	30,00 €
Acidification of soil and water	kg SO_2-eq	4,00 €
Eutrophication	kg PO_4^{3-}-eq	9,00 €
Depletion of abiotic resources – elements	kg Sb-eq	0,16 €
Depletion of abiotic resources – fossil fuels	kg Sb-eq	0,16 €
Human toxicity	kg 1,4 DB-eq	0,09 €
Freshwater ecotoxicity	kg 1,4 DB-eq	0,03 €
Marine water ecotoxicity	kg 1,4 DB-eq	0,0001 €
Terrestrial ecotoxicity	1,4 DB-eq	0,06 €
Photochemical oxidant creation (Smog)	kg C_2H_4	2,00 €

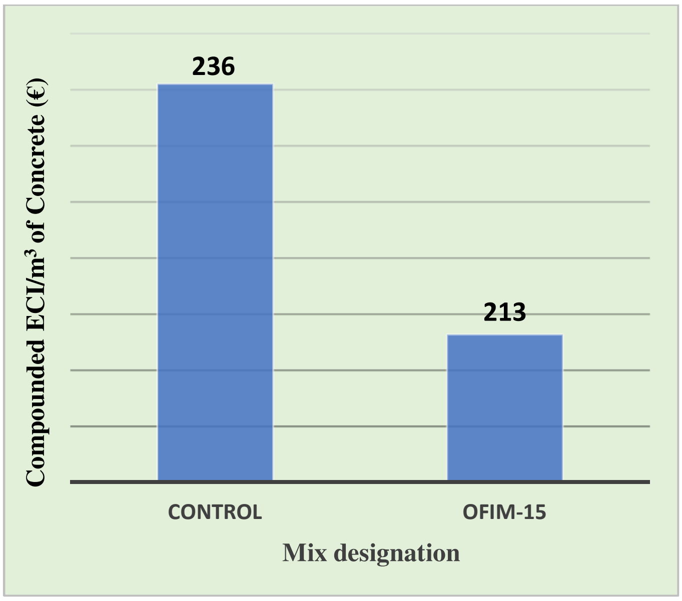


Figure 18 Compounded ECI of assessed concrete mixes per cubic meter

5. CONCLUSIONS

The study reported in this paper assesses the effect of *Ofim* on the plastic and hardened-state properties of modified concrete mixes. Modified concrete mixes with the bio-additive and a chemical admixture (SIKA) were investigated relative to a control mix. Independent experiments were conducted with determined percentages of water mass replacements with *Ofim* (15%, 25% or 50%), and the dosage of the plasticizer (SIKA). SEM and FTIR were conducted to study respectively the microstructure of the *Ofim* modified concrete and the interaction between the bio-additive constituents and cement. Furthermore, a comparative Environmental Life Cycle Assessment (E-LCA) was conducted to assess resource use efficiency and to quantify the environmental impacts of *Ofim*-modified concrete relative to conventional concrete. The main conclusions from the study are:

1. Incorporation of *Ofim* into concrete variably affected different strength parameters at every age of testing. Enhancement of mechanical properties by *Ofim* water mass-replacement was significant at 56 days. At 56 days, enhancement of mechanical strength properties reduced with increase in *Ofim* water-replacement percentage. The study noted no significant effect of *Ofim* on the modulus of elasticity and standard flexural strength of concrete. The difference in mechanical strength results of *Ofim*-modified at older ages of testing are indicative of the retarding effect of *Ofim* in concrete and related strength generation, with an anticipation of possible better enhancement after 90 days of curing.
2. Interaction of *Ofim* and SIKA plasticizer in concrete resulted into significant strength enhancement relative to the independent effects of each in concrete. A mixing water mass replacement of 15% with *Ofim*, enhanced slump of SIKA-1.5 plasticized concrete by 19.5% and compressive strength by 35.4%. *Ofim* is a desirable performance enhancer in plasticized concrete mixes.
3. Interaction of *Ofim*-15 and SIKA-1.5 produced concrete with a quasi-pozzolanic activity, as evidenced by ettringite formation seen in SEM backscatter images of 56-day old concrete samples. Furthermore, interaction of cations present in cement with the bio-polymeric constituents present in the bioadmixture were evidenced by FTIR spectra, and contributed to the properties enhancement in modified concrete mixes.
4. It was evident in durability tests conducted on selected mixes that *Ofim*-modified concrete is a durable material with water absorption/ingresses reduced between 14% and 39% relative to the control mix, with minimum rate of water ingress noted with a 25% of mixing-water replacement with *Ofim*. *Ofim*-modified mixes deteriorated at a very low rate when exposed to freeze-thaw cycles, retaining 83% of the initial RDME compared to conventional concrete which retained only 55% after 180 freeze-thaw cycles. The study significantly noted better insulating properties in *Ofim*-modified mixes with reduced K-values between 9% and 14% relative to the control mix.
5. Production of *Ofim*-modified concrete with 15% water mass replacement reduced the environmental impact by an average of 9.6%, leading to ECI cost savings of 22 € per cubic meter relative to conventional concrete, based on the Percentage-point Cement Reduction (APCR) method of strength performance leveling. This reduction is significant as construction materials contribute a huge share of the global GHG emissions, specifically from embodied carbon (13%). Any reduction of the carbon footprint from the

production of cement-based materials will play a substantial role in the global reduction of CO_2 emissions and help mitigate climate change.

This study therefore concludes that *Ofim*-modified concrete is a more durable and environmentally responsible material than conventional concrete. Experiments at the level of material performance of *Ofim*-modified concrete, provide promising insight for its adoption in the fast-evolving infrastructure industry, given the current concerns on climate change and advocacy for design for circular economies. Future research is needed to evaluate the structural performance of *Ofim*-modified concrete full-scale members designed to fail in flexure, shear, or bond splitting modes of failure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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