

Valorization of Olive Kernel Shell Waste as Partial Aggregate Replacement in Self-Compacting Concrete

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Abstract:

Olive oil production in the Mediterranean region generates large quantities of agro-industrial byproducts, posing environmental challenges. This study investigates the use of olive kernel shells (OKS) as a partial replacement for coarse aggregates in the production of self-compacting concrete (SCC) to enhance sustainability and reduce waste. OKS were oven-dried, conditioned to the laboratory air-dry state, and incorporated at 5–25% replacement levels by aggregate volume. The fresh and hardened properties of SCC were evaluated following EFNARC and ASTM standards. Results show that slump flow decreased from 700 mm (control) to 550 mm (25% OKS) due to higher water absorption of OKS, while fresh density declined from 2548 kg/m³ to 2015 kg/m³, confirming the lightweight nature of the mixes. Segregation resistance improved with higher OKS content, dropping from 22% to 12%. In hardened concrete, dry density reduced from 2429 kg/m³ to 1949 kg/m³, and ultrasonic pulse velocity (UPV) decreased from 4.8 km/s to 3.2 km/s. The compressive strength at 28 days decreased from 55 MPa (control) to 28 MPa (25% OKS), while the 5% OKS mixture retained the highest mechanical performance among the tested replacement levels, achieving 50 MPa compressive and 4.8 MPa flexural strength, suitable for lightweight structural applications. These findings demonstrate that incorporating up to 5% OKS as a coarse aggregate replacement can produce eco-efficient, lightweight SCC with acceptable mechanical performance.

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1. INTRODUCTION

Today, the construction industry contributes more than ever to the depletion of natural aggregates such as sand and gravel, which are

essential components of mortar and concrete mixtures. The excessive extraction and consumption of these materials are leading to their gradual scarcity and price instability [1, 2]. To help preserve natural resources, the use of agricultural

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waste materials as partial substitutes for traditional aggregates offers an environmentally friendly and economically viable alternative [3–5]. The rapid accumulation of agricultural residues has become a serious environmental concern, and their proper management can significantly mitigate ecological impacts. Consequently, researchers worldwide have increasingly focused on the development of sustainable construction materials derived from agricultural by-products with suitable mechanical and thermal properties. Studies have demonstrated the feasibility of incorporating wastes such as corn straw [6–8], sugarcane bagasse [9–11], wheat and rice straw [12], biomass ash [13], sorghum stalks [14], and miscanthus [15] as raw materials in civil engineering applications, particularly as partial replacements for cement or sand in concrete and mortar production.

During the past decade, several studies have explored concrete and mortar incorporating agricultural wastes. Pineapple, a typical tropical fruit, generates crown waste that is rarely utilized [16]. However, using these fibers in concrete is limited by extraction and impurity issues [17]. NaOH treatment effectively removes non-cellulosic compounds [18] but raises environmental and cost concerns [19]. This treatment improves fiber–cement adhesion, similar to effects observed with other natural fibers like coconut [20]. De Araujo Alves Lima et al. [21] further reported that the optimal chemical treatment depends on fiber type, with combined alkalization and salinization proving most effective for sisal.

Likewise, sugarcane—a major source of sugar and alcohol—produces significant waste, especially during the COVID-19 pandemic when alcohol production increased [22]. Although commonly used as animal feed, its low value limits research interest. Some studies have focused on burning sugarcane bagasse and using the resulting ash as a cement additive [23]. Agro-waste ash is among the most explored supplementary materials in construction, with findings showing that burning temperature strongly affects ash quality and, consequently, mortar and concrete performance [24].

Similarly, rising construction costs in developed countries have encouraged the use of alternative materials such as coconut shells, which offer a sustainable aggregate source and help reduce agro-waste [25]. Small shells (20–600 mm) can serve as aggregates, while coconut fibers can be used as fillers or reinforcement due to their structural

properties. Experimental studies show that these fibers help absorb internal stresses in mortars [26]. Hasan et al. [27] observed that incorporating 20% coconut shell aggregate reduced compressive strength, but mixes containing up to 50% still met standard requirements.

Another widely studied agricultural residue is rice husk, which is produced in large quantities and poses disposal and pollution problems [28]. Burning husks emits pollutants, while landfilling generates methane that contributes to global warming. Some countries use rice husks for energy production, generating ash rich in amorphous silica and carbon [29]. This ash enhances the compressive strength of foamed concrete by up to 70% and improves impact energy absorption at 5–20% replacement levels. However, higher ash contents reduce workability due to increased porosity and water absorption, though they also lower thermal conductivity.

Despite extensive research on agro-waste utilization in concrete, studies specifically addressing the incorporation of OKS into SCC remain scarce. Most existing works have focused on conventional concrete or other agricultural by-products such as coconut, rice husk, or bagasse, while the potential of OKS, an abundant by-product of the olive oil industry, has not been thoroughly explored. This study therefore introduces a novel approach by evaluating the feasibility of using OKS as a partial coarse aggregate replacement in SCC. The work aims to assess the influence of different OKS substitution levels on the fresh and hardened properties of SCC, thereby contributing to sustainable construction practices and the valorization of olive industry waste.

2. MATERIALS AND METHODS

This section outlines the characteristics of the raw materials, the mixing proportions, and the testing procedures. The experimental program comprises three main stages: material preparation, concrete mix production for specimen casting, and subsequent testing of the SCC samples. A detailed description of each stage is provided in this subsection.

2.1. Materials

This study employed Ordinary Portland Cement (OPC), commercially known as AL-Mass, conforming to ASTM C150 [30] standards. The chemical composition of the cement is presented in Table 1.

Grade 53 OPC, with a specific gravity of 3.15 and a standard consistency of 31.5%, was used. Additionally, limestone powder (LP) possessing a specific gravity of 2.68 and a particle size smaller

than 75 μm was incorporated as a partial replacement of cement by weight in the SCC mixtures.

Table 1. Chemical Properties of Cement

Components	CaO	SiO ₂	K ₂ O	Fe ₂ O ₃	MgO	Na ₂ O	Al ₂ O ₃
Percentages (%)	62.3	20.28	0.75	4.2	2.6	0.4	5.55

Both coarse and fine aggregates were employed in this experimental program, and their properties were evaluated in accordance with ASTM C33 [31] standards. The fine aggregate had a maximum particle size of 5 mm, a specific gravity of 2.54, a fineness modulus of 2.5, a sulfate (SO₃) content of 0.18%, and a water absorption rate of 0.82%. The grading of the fine aggregate is presented in Table 2. Clean gravel, with a maximum size of 14 mm, a specific gravity of 2.68, a sulfate (SO₃) content of 0.04%, and a water absorption rate of 0.28%, was used as the coarse aggregate. The grading curve of the coarse aggregate is shown in Table 3.

which had a specific gravity of 0.91, determined in accordance with ASTM C127 [32]. After pulp extraction, the OKS was thoroughly washed with water and then oven-dried at 100 °C for 48 h.

Following oven-drying, the OKS was conditioned at ambient laboratory temperature to an air-dry state prior to batching and was incorporated into the mixtures in this condition. No additional mixing water was added to compensate for the water absorption of the OKS particles. The reported water-to-binder ratio therefore reflects the gross (total) batching water rather than an absorption-adjusted effective water content.

Table 2. Particle-size distribution of fine aggregate

Sieve size (mm)	Passing (%)	Limitations
10	100	100
5	97	89-100
2.36	82	60-100
1.18	67	30-100
0.6	51	15-100
0.3	22	5-70
0.15	2.5	0-12

Table 3. Particle-size distribution of coarse aggregate

Sieve size (mm)	Passing (%)	Limitations
14	100	100
10	86.76	85-100
5	14.12	0-25

The olive kernel waste used in this study was sourced from an oil production factory in Iraq. Fig. 1 shows the OKS employed in the experiment,



Fig. 1. Olive Kernel Shells (OKS)

The chemical composition of the OKS is summarized in Table 4.

Table 4. Chemical Properties of OKS

Components	CaO	SiO ₂	K ₂ O	Fe ₂ O ₃	MgO	Na ₂ O	Al ₂ O ₃
Percentages (%)	5.72	57.4	4.09	6.2	3.16	2.37	17.98

The superplasticizer used in this study served as an effective water-reducing admixture for enhancing the rheological performance of the concrete mixtures. It was based on a modified polycarboxylate formulation, fully soluble in water. A dosage of 7 kg/m³ of cementitious material was incorporated to improve the flowability and

workability of the SCC. The superplasticizer, Sika ViscoCrete-5930, was supplied by Sika Corporation. The main properties of the superplasticizer are presented in Table 5.

Table 5. Properties Sika® ViscoCrete®-5930 L IQ superplasticizer [13]

Technical Data	Results
Form	Viscous Liquid
Color	Brownish Liquid
Specific Gravity	1.085±0.01
pH	4 to 6

2.2. Mixture Design Proportions

The mix design involves selecting the optimal and economical constituents for the SCC mixture and establishing their respective proportions to enhance fresh and mechanical characteristics. The study included six different mixed formulations. The target 28-day strength was set between 30 and 50 MPa. Six mixes were cast with fixed amounts of cement (350 kg/m³), limestone (150 kg/m³), sand (790 kg/m³), water (170 kg/m³), and varying percentages of coarse aggregate and OKS (5, 10, 15, 20, and 25) %, as shown in Table 6. The superplasticizer dosage (7 kg/m³) was likewise held constant across all mixtures, following the base mix design. It was not increased to offset the additional water demand associated with higher OKS replacement levels.

Table 6. Mixture proportion ratios for 1 m³

Mix ID	Coarse Aggregate (kg/m ³)	Olive Kernel (kg/m ³)	W/C	SP (kg/m ³)
OKS0%	965	0	0.49	7
OKS5%	818	50	0.49	7
OKS10%	730	80	0.49	7
OKS15%	658	105	0.49	7
OKS20%	600	125	0.49	7
OKS25%	565	142	0.49	7

2.3. Sample Preparation, Casting and Curing

In this study, a pan mixer was employed to prepare the SCC mixtures. Cube specimens with dimensions of 100 × 100 × 100 mm were cast to evaluate dry density, UPV, and compressive strength, and prism specimens measuring 500 × 100 × 100 mm were cast to evaluate flexural strength, in accordance with BS EN 12390-5 [33]. For each mixture, three cube specimens were tested for compressive strength at each curing age (7 and 28 days), and three prism specimens were tested for flexural strength at 28 days, with the reported values representing the average of three replicates. Dry density and UPV were each measured on a single specimen per mixture. The mixing process began by placing the freshly prepared mix into the

pan mixer, after which the molds were filled in three layers. Each layer was compacted using a vibrating table to ensure optimal density and uniform compaction until a workable concrete mix was achieved. After casting, the specimens were left undisturbed for 24 h. They were then demolded and submerged in a curing tank maintained at 25 ± 2 °C for 28 days. During the initial 24-hour period, the cast specimens were stored in a humid cabinet at 25 ± 2 °C and a relative humidity of not less than 95%. The quantities of materials used for each batch of the concrete mix and for specimen casting were carefully controlled throughout the process.

2.4. Test Methods

Fresh concrete is defined by its flowability, mobility, and cohesiveness. The term workability is commonly used to describe these fresh-state properties. In this study, the filling capacity of SCC was assessed through measurements of fresh density (kg/m³) and slump flow (mm). Segregation resistance tests were conducted to evaluate the mixture's viscosity and flow stability, ensuring a uniform composition. All fresh concrete tests were performed in accordance with ASTM standards, and the obtained results were compared with the EFNARC guidelines [34].

The slump flow test was used to determine the initial flow characteristics of fresh SCC. The procedure involved filling a standard slump cone without any external compaction, then lifting it vertically and measuring the average spread diameter of the concrete in two perpendicular directions. This test provided an indication of the SCC's unrestricted deformability and flowability. The slump flow and segregation resistance tests were each performed once per mixture immediately after mixing, consistent with standard fresh-state SCC characterization practice.

The segregation resistance of fresh SCC was evaluated using the GTM screen stability test developed by the French contractor GTM. In this method, 10 L of SCC was placed in a bucket, covered to prevent evaporation, and left to rest for 15 min. A 5 mm sieve (350 mm in diameter) was then placed on a sieve pan positioned on a weighing scale, and approximately half of the SCC sample was poured onto it. After 2 min., the quantity of mortar passing through the sieve was weighed and expressed as a percentage of the initial sample mass retained on the sieve.

After completing the preliminary concrete tests, the fresh SCC mixtures were poured into molds. To evaluate the hardened properties, the specimens

were demolded 24 h after casting and then cured in water for 28 days. Bulk density was determined in accordance with ASTM C642 [35], while UPV measurements were conducted following ASTM C597-09 [36]. The compressive strength of three 100 mm cube specimens was tested and averaged at 7 and 28 days, in compliance with BS EN 12390-3 [37], and the flexural strength of three prism specimens was tested and averaged at 28 days, in compliance with BS EN 12390-5 [33].

3. RESULTS AND DISCUSSION

3.1. Fresh Properties

The fresh properties of the SCC specimens were evaluated in accordance with EFNARC [34] standards. This assessment ensured that the prepared concrete mixtures met the standard requirements for SCC.

According to EFNARC guidelines, the slump flow diameter for SCC should range between 650 and 800 mm. As shown in Fig. 2, the slump flow diameter decreased with the increase in OKS aggregate content. This reduction is attributed to the higher water absorption capacity, angularity, and surface roughness of OKS aggregates compared to conventional aggregates, which increase internal friction between the cement paste and the aggregate, thereby limiting the flow of the mixture. It should be noted that the SP dosage was not adjusted to compensate for the increased water demand associated with higher OKS content. Consequently, part of the observed reduction in slump flow may also reflect a relative under-dosing of superplasticizer at higher replacement levels, in addition to the aggregate's absorption, angularity, and surface roughness effects discussed above.

EFNARC classifies SCC slump flow diameters into three categories: SF1 (550–650 mm), SF2 (650–750 mm), and SF3 (750–850 mm). As illustrated in Fig. 2, most of the recorded slump flow diameters fall within the SF1 range, which is appropriate for various structural applications such as walls, columns, and blocks. Despite the observed reduction, all mixes complied with EFNARC's slump flow classifications, with the control mix (OKS0) falling under the SF2 category.

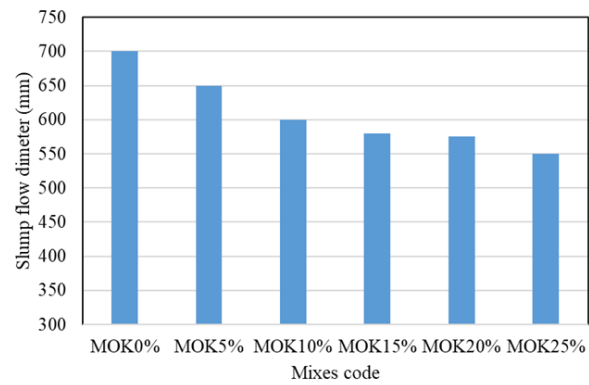


Fig. 2. Slump values of SCC samples containing different replacement levels of OKS

The sieve segregation test evaluates the segregation resistance of SCC by placing fresh concrete on a 5 mm sieve and measuring the amount of mortar or paste that passes through it [38]. For mixtures incorporating OKS as a replacement, the segregation ratio varied between 22% and 12%, decreasing progressively with higher OKS content, as illustrated in Fig. 3. The maximum segregation ratio (22%) was observed in the control mix (0% OKS), while the minimum ratio (12%) was recorded at 25% OKS replacement. This decline in segregation ratio can be attributed to the increased water absorption of OKS particles, which enhances the plastic viscosity of the mixture, thereby reducing aggregate settlement and improving segregation resistance [39].

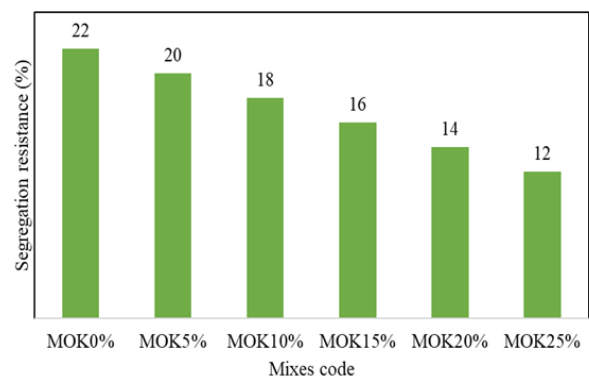


Fig. 3. Segregation resistance values of SCC samples containing different replacement levels of OKS

The fresh density results of SCC mixtures incorporating OKS are presented in Fig. 4. The initial density of SCC is largely affected by several factors, including the specific gravity of the cement, the properties of the aggregates, and the type and amount of admixtures in the cementitious matrix. The specific gravity plays a significant role in determining the workability and compactness of SCC.

In this study, a constant water-to-binder ratio (w/b) was maintained, along with fixed quantities of superplasticizer, fine aggregate, and cement. The coarse aggregate was partially replaced with OKS at levels of 5%, 10%, 15%, 20%, and 25% by weight. The results revealed a gradual reduction in fresh density with increasing OKS content. The control mix (OKS0%) exhibited the highest fresh density of 2548.1 kg/m³, while the mix containing 25% OKS (OKS25%) recorded the lowest density at 2014.8 kg/m³. This decrease in density can be attributed to the lower specific gravity of OKS, measured at 0.91, which is significantly less than that of conventional coarse aggregates. This value is broadly consistent with, though somewhat lower than, values reported for other agro-industrial shell aggregates used as lightweight aggregate in concrete or mortar, such as oil palm kernel shell (typically 1.1–1.4) [40]. This difference may reflect the distinct cellular structure and lower density of olive kernel shell relative to palm-based shells, as well as the air-dry (rather than SSD) condition of the OKS at the time of testing.

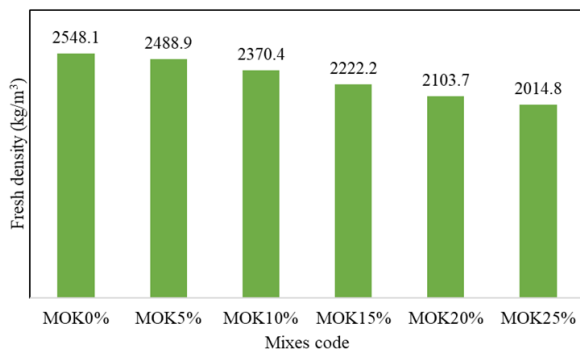


Fig. 4. Fresh density results of SCC samples containing different replacement levels of OKS

3.2. Hardened Properties

Fig. 5 presents the dry density results after 28 days, which ranged from 2429.6 to 1949.6 kg/m³. The findings indicate a clear decrease in hardened density with increasing OKS content, primarily due to the lower specific gravity of OKS compared to natural coarse aggregates. This reduction reflects the lighter nature of the OKS material, which contributes to an overall decrease in the concrete's bulk density.

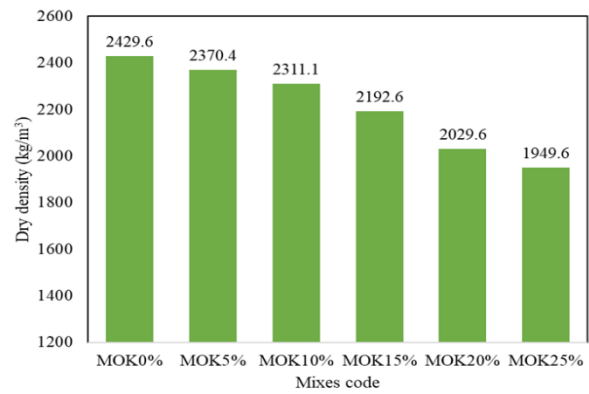


Fig. 5. Dry density results of SCC samples containing different replacement levels of OKS

The UPV results for composites containing different proportions of OKS particles, along with their classification according to IS 13311-1 [41], are presented in Fig. 6. After 28 days of curing, the UPV values exhibited a consistent decline with increasing OKS content. Specifically, the reductions in UPV compared to the control mix (OKS0) were approximately 12.5%, 16%, 20.8%, 27%, and 33.3% for OKS5, OKS10, OKS15, OKS20, and OKS25, respectively.

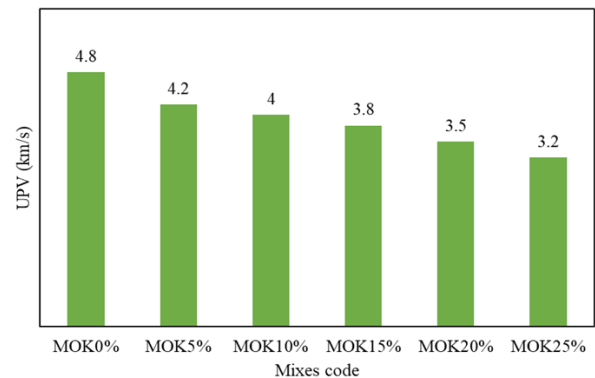


Fig. 6. UPV results of SCC samples containing different replacement levels of OKS

This decrease in UPV can be attributed to the rough texture and porous nature of OKS particles, which contribute to greater internal voids within the cement matrix, resulting in ultrasonic wave attenuation. Similar trends were observed by Abutaha et al. [42] in mixtures containing palm oil clinker aggregates and by Memon et al. [43] in concretes with porous corncob particles. Chahour et al. [44] further noted that UPV measurements reflect the acoustic characteristics of materials [45], implying that UPV values can serve as indicators of the sound insulation potential of self-compacting lightweight mortars. Additionally, UPV values tend to increase with curing age due to the progressive

densification of the concrete matrix, moisture retention, and extended hydration.

Fig. 7 presents the compressive strength results of SCC mixtures containing various OKS replacement levels, tested at 7 and 28 days. As illustrated in Fig. 7, an increase in OKS content resulted in a noticeable reduction in compressive strength. After 28 days of curing, the compressive strength decreased by approximately 9%, 16.4%, 29%, 41.8%, and 49% for OKS5%, OKS10%, OKS15%, OKS20%, and OKS25%, respectively, compared to the control mix (OKS0%).

The decline in compressive strength is primarily attributed to the physical and geometrical characteristics of the OKS particles, which create localized weak zones within the concrete matrix [46]. Additionally, the high water absorption capacity of these particles increases the amount of entrapped air in the fresh mix, resulting in higher porosity in the hardened concrete [47].

It should be noted that the OKS were used in an air-dry condition, and no additional water was added to compensate for their absorption. Therefore, the reported water-to-binder ratio represents the total mixing water and does not account for the water absorbed by the OKS. During mixing, the OKS may have absorbed part of the available water from the fresh paste, reducing the effective water available for cement hydration and contributing to the reduction in slump flow observed in Section 4.1. This effect may be more important than the influence of particle shape or surface texture alone. On the other hand, porous lightweight aggregates can release part of the absorbed water during hydration and provide some internal curing effect [48]. In the present study, however, the amount of water absorbed by the OKS was not used to adjust the mix water or to provide a controlled internal curing reservoir. As a result, the possible effects of water loss from the paste and subsequent internal curing cannot be separated.

These observations are consistent with previous studies. For instance, Wu et al. [49] observed a strength reduction of 25.1% and 44% for 50% and 100% peach shell replacements, respectively. Furthermore, Olanipekun et al. [50] demonstrated that complete replacement with oil palm kernel shells led to significantly diminished mechanical strength.

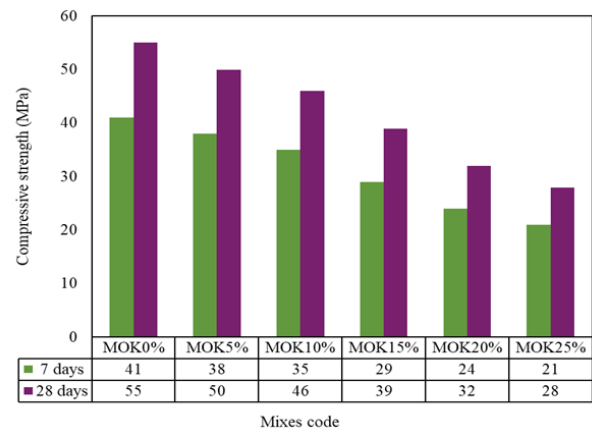


Fig. 7. Compressive strength results of SCC samples containing different replacement levels of OKS

Fig. 8 presents the variations in the tensile and flexural strength of SCC incorporating different proportions of OKS as a partial aggregate replacement. The observed trends in tensile strength closely follow those of compressive strength, showing a consistent decrease as the OKS replacement level increases.

As illustrated in Fig. 8, the flexural strength of SCC mixtures declined progressively with higher OKS substitution rates. After 28 days of curing, the reductions in flexural strength were approximately 14.3%, 28.6%, 37.5%, 46.4%, and 53.6% for OKS5%, OKS10%, OKS15%, OKS20%, and OKS25%, respectively, compared to the control mix (OKS0%).

This reduction in flexural strength is primarily attributed to the porous and brittle nature of the OKS aggregates, their relatively low density compared to natural aggregates, and their weak interfacial bond with the cement matrix [51]. Similar findings were reported by Sathiparan and De Zoysa [52], who also observed a decrease in flexural strength with higher replacement levels of organic or lightweight waste aggregates.

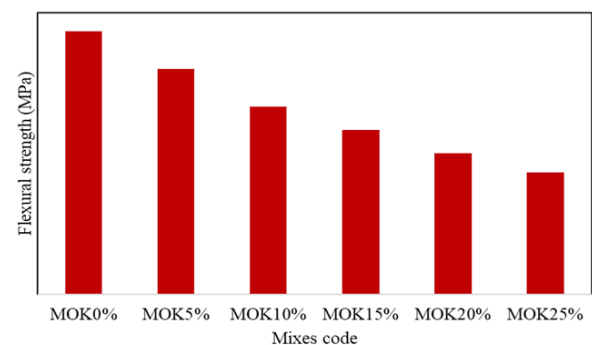


Fig. 8. Flexural strength results of SCC samples containing different replacement levels of OKS

Although SCC incorporating OKS exhibits reduced mechanical performance, such composites

can still be suitable for applications where strength requirements are moderate, such as in non-structural elements, cementitious blocks, and screeds. These conclusions align with the results of Barreca and Fichera [53].

It is important to note that the mechanistic explanations proposed above for the observed trends in UPV, compressive strength, and flexural strength (including internal void formation, localized weak zones, weakened interfacial bonding, and the limited internal curing contribution discussed above) are interpretive and consistent with mechanisms reported for other porous agro-waste aggregates in the literature. These explanations were not directly corroborated in the present study through microstructural techniques (SEM, EDS, XRD...) or quantitative porosity/void-content assessment, and should therefore be regarded as plausible interpretations rather than confirmed mechanisms. Fig. 9 summarizes the main properties of the concrete mixtures and shows the changes in workability, density, UPV, and mechanical strength with increasing OKS replacement.

Effect of OKS Replacement on Fresh and Hardened Properties									
Mix ID	OKS Replacement (%)	Slump Flow (mm)	Segregation Resistance (%)	Fresh Density (kg/m ³)	Dry Density (kg/m ³)	UPV (km/s)	Compressive Strength, 7d (MPa)	Compressive Strength, 28d (MPa)	Flexural Strength, 28d (MPa)
MOK0%	0	700	22	2548.1	2429.6	4.8	41	55	5.6
MOK5%	5	650	20	2488.9	2370.4	4.2	38	50	4.8
MOK10%	10	600	18	2370.4	2311.1	4.0	35	46	4.0
MOK15%	15	580	16	2222.2	2192.6	3.8	29	39	3.5
MOK20%	20	575	14	2103.7	2029.6	3.5	24	32	3.0
MOK25%	25	550	12	2014.8	1949.6	3.2	21	28	2.6

Fig. 9. Summary of the fresh and hardened properties of concrete mixtures with different OKS replacement levels

4. RELATIONSHIP BETWEEN THE TESTED PROPERTIES

The experimental data collected in this study were used to establish correlations among various parameters and for the development of empirical equations for predicting the corresponding properties of SCC. Based on the results, a strong direct relationship was observed between the

compressive strength and the dry density of SCC incorporating OKS, expressed by the empirical equation with six data points (n=6):

$$\rho_{dry} = 17.06f_c + 1473.6 \quad (1)$$

where ρ_{dry} is the dry density (kg/m³) and f_c is the 28-day compressive strength (MPa). The derived relationship is illustrated in Fig. 10.

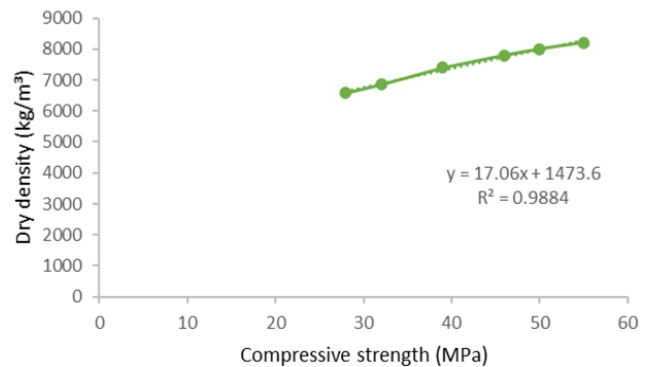


Fig. 10. Relationship between compressive and dry density

Furthermore, the UPV exhibited a strong direct correlation with the compressive strength of SCC incorporating OKS, expressed by the empirical equation:

$$UPV = 0.0517f_c + 1.7605 \quad (2)$$

where UPV is in km/s and f_c is the 28-day compressive strength (MPa). Fig. 11 provides a graphical representation of the relationship between compressive strength and UPV.

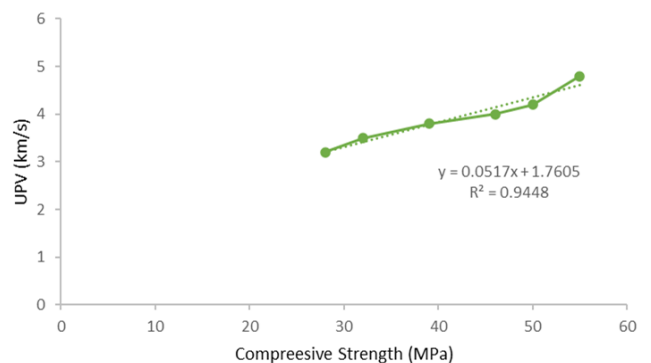


Fig. 11. Relationship between compressive strength and UPV

Both regressions were statistically significant ($p < 0.05$), and the high R^2 values (>0.94) indicate that dry density and UPV are reliable indirect predictors of compressive strength for OKS-based SCC within the tested replacement range (0–25%). However, given the limited number of data points ($n = 6$, one per replacement level), these equations should be regarded as preliminary and validated against a

larger, independently cast dataset before wider application.

5. LIMITATIONS OF THE STUDY

This study has several limitations that should be considered when interpreting the results.

First, the investigation was conducted at laboratory scale using OKS obtained from a single source. Potential variations in particle size, density, porosity, moisture content, and surface characteristics among different OKS sources were therefore not captured, and the findings may not be directly transferable to OKS from other regions or processing conditions.

Second, only replacement levels between 5% and 25% were examined under a fixed mixture design. The effects of alternative water-management strategies, such as OKS pre-saturation, moisture-conditioning protocols, or systematic adjustment of mixing water to maintain a constant effective water-to-binder ratio, were not investigated. Similarly, the superplasticizer dosage was held constant at 7 kg/m³ and was not optimized for each replacement level. As a result, the observed reduction in slump flow with increasing OKS content may reflect a combination of aggregate-related effects (absorption, angularity, surface texture) and relative superplasticizer under-dosing at higher replacement levels.

Third, the experimental program focused primarily on fresh properties (slump flow, segregation resistance, fresh density) and a limited set of hardened properties (dry density, UPV, compressive strength, and flexural strength). Other potentially relevant mechanical characteristics, such as splitting tensile strength, elastic modulus, shrinkage, creep, and bond behavior to reinforcement, were not evaluated.

Fourth, long-term durability performance was not addressed. Properties such as water absorption, capillary suction, permeability, chloride-ion penetration, sulfate resistance, carbonation depth, and freeze-thaw resistance remain unknown for OKS-based SCC and should be examined before structural or exposure-critical applications are considered.

Fifth, no microstructural characterization was performed. Techniques such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD), or quantitative image analysis were not used, which limits direct assessment of the interfacial transition zone (ITZ), pore structure, and the mechanisms

responsible for the observed reductions in UPV and mechanical strength. The mechanistic explanations provided in the Results and Discussion section should therefore be regarded as plausible interpretations consistent with the literature on porous agro-waste aggregates, rather than experimentally verified mechanisms.

Sixth, the empirical correlations between dry density, UPV, and compressive strength are based on a single dataset comprising six mixtures. These relationships should be considered preliminary and must be validated against larger, independently cast datasets before being used for predictive or design purposes.

Seventh, slump flow, segregation resistance, dry density, and UPV were each measured on a single specimen or sample per mixture, rather than in triplicate. This limits the ability to quantify measurement variability and statistical uncertainty for these parameters. In contrast, compressive and flexural strength were each based on the average of three specimens, but individual specimen-level data were not retained, precluding the reporting of standard deviations.

Eighth, the possible contribution of OKS to internal curing, arising from their high water absorption, was not experimentally isolated. A systematic comparison of oven-dry, air-dry, and pre-saturated OKS conditions, combined with monitoring of internal relative humidity or autogenous deformation, would be required to separate water-loss effects from potential internal-curing benefits.

Finally, the identification of a preferred OKS replacement level in this study was based solely on mechanical strength retention relative to the control mix. A comprehensive techno-economic and environmental assessment, including cost per unit strength, embodied carbon, life-cycle impacts, and waste-valorization potential, was outside the scope of this work. Such an assessment is recommended for future research to support practical mix-design decisions and to position OKS-based SCC within broader sustainability frameworks.

Collectively, these limitations highlight the need for further studies addressing OKS source variability, durability, microstructure, long-term performance, and holistic sustainability criteria before broader engineering application can be recommended.

6. CONCLUSION

This study investigated the feasibility of using OKS, an abundant by-product of the olive oil

industry, as a partial replacement for coarse aggregates in SCC. The experimental program evaluated the influence of various OKS replacement levels (5–25%) on the fresh and hardened properties of SCC, including slump flow, segregation resistance, density, ultrasonic pulse velocity, and mechanical strength.

The results demonstrated that incorporating OKS led to a gradual reduction in both fresh and dry densities, confirming the potential for the development of lightweight SCC. Slump flow values decreased with higher OKS content due to the shells' high water absorption and rough texture, while segregation resistance improved, indicating enhanced stability. In the hardened state, both compressive and flexural strengths declined with increasing OKS content. Among the replacement levels studied, the 5% OKS mixture showed the closest compressive and flexural strength to the control mix, with values of about 50 MPa and 4.8 MPa, respectively. This level may therefore be suitable for lightweight structural applications requiring moderate to high strength. However, the choice of OKS content should not be based on strength alone. All replacement levels (5–25%) met the EFNARC SF1 workability classification, while segregation resistance improved as the OKS content increased. Therefore, the appropriate replacement level will depend on the strength, workability, and durability requirements of the intended application, as well as economic and environmental factors, which were not investigated in this study. These findings confirm that limited substitution of natural aggregates with OKS can yield eco-efficient SCC with adequate workability and strength characteristics.

For future work, further studies are recommended to examine the durability performance of OKS-based SCC under various exposure conditions, including freeze–thaw cycles, chloride penetration, and sulphate attack. The optimization of surface treatments to improve interfacial bonding, as well as microstructural analyses using SEM and XRD, should also be pursued. Moreover, life-cycle assessment and cost–benefit analyses would provide valuable insights into the environmental and economic advantages of large-scale implementation of OKS in sustainable construction.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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