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Review

Systematic review on the use of waste foundry sand as a partial replacement of natural sand in concrete

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ABSTRACT

Waste foundry sand (WFS) is a by-product of the metal casting process, which constitutes a sustainable solution as a replacement for natural sand (NS) in the production of concrete. This article provides an overview of two types of WFS, along with their physical and chemical properties. The present research highlights the potential applications of WFS in mortars, concrete, and self-compacting concrete (SCC). In addition to examining the influence of WFS substitution on workability, mechanical properties, and durability. The literature consulted indicates that the workability, mechanical properties, and durability of mortar, concrete, and SCC may be affected when increasing the substitution of NS with WFS. However, in some cases, WFS can offer comparable or improved mechanical and durability properties to NS. It has been observed that in some studies, impurities in the form of clay particles, dust, and phenolic resins of the WFS particles are the reason for the resulting decrease reported in workability, mechanical properties, and durability. Few studies report durability in terms of ultrasonic pulse velocity (UPV), freeze-thaw resistance, abrasion, chloride penetration, and sulphate resistance, which is a research gap that should be addressed. Moreover, the use of WFS is a viable alternative to NS, leading to a more sustainable and environmentally friendly approach for the construction industry.

1. Introduction

The construction industry has a profound effect on the environment, accounting for more than 50% of the exploitation of natural resources [1], such as coarse and fine aggregates, and is responsible for 39% of carbon dioxide (CO_2) emissions [2]. To address this issue, researchers have explored alternative materials, including recycled aggregates (RA) derived from demolition and construction waste, which have been widely studied in different cement-based materials, particularly in conventional and SCC. Another potential alternative material is foundry sand (FS) [3]. The use of FS in concrete promises to resolve the issue of waste utilization and makes considerable progress toward the zero-waste goal [4]. It has been reported that the use of FS improves the quality of concrete, making it denser [5] and durable [6] compared to the reference concrete, thus being a feasible alternative to the use of fine natural aggregates.

FS is also known as a siderurgical aggregate (SA) in academic literature [7]. The relationship between FS and SA may be related to the utilization of FS as an aggregate in siderurgical or metallurgical applications, particularly in the production of iron and steel. The performance of SA in cement-based materials depends on various factors, such as the substitution percentage, water/cement ratio (w/c), and characteristics of the aggregates. Incorporating SA into cement-based materials provides a way to use potential aggregates that would otherwise end up in landfills, thereby prolonging their useful life. This approach both reduces the exploitation of natural resources and results in cement-based materials with similar characteristics to those made with natural aggregates. Overall, the use of alternative materials such as RA and SA are crucial for mitigating the environmental effects of the construction sector. By exploring and utilizing these materials, researchers can contribute to the development of sustainable construction practices that preserve natural resources and minimize waste.

Metal casting is a traditional method that is widely used in various industries including automotive, aerospace, and machine component manufacturing. This process is commonly used for casting ferrous materials such as iron and steel, as well as non-ferrous materials like brass, bronze, and aluminum [8]. FS is the primary material used for making sand molding boxes. These boxes are created by compressing two molds,

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an upper and a lower one full of agglomerated sand, against a solid object made of wood, plastic, or metal [9], making this object a replica of the part to be manufactured. Once the compaction procedure is complete, the molds are briefly separated to remove the part and then rejoined to form a single mold with a cavity inside. Molten metal is then poured into the mold box, where it solidifies. The sand box is then removed and disintegrated by mechanical means for later reuse. The FS is broken down and reused in the casting process until its properties are no longer suitable for use, typically about either 3–4 times [10] or 8–10 times [11]. Fig. 1 provides a schematic diagram of the manufacturing process for parts using this method.

The WFS results from valorizing FS residue. The valorization process involves determining its granulometric, chemical, and physical properties. Particle size distribution (PSD) influences key aspects such as workability, mechanical strength, and durability of materials, exerting a direct influence on the integrity and performance of built structures. The physical properties of WFS are related to mortar and concrete performance. It is crucial to determine WFS density and absorption, as these properties can alter density when replacing NS and affect mix workability due to its high WFS absorption. Regarding the chemical composition aspect, it is essential to analyze WFS elements using XRD or XRF, since mechanical behavior and durability of mortar or concrete can be explained based on these results.

It is estimated that the generation of WFS is 100 million tons (Mt) annually [12] and that for each ton of steel produced, 0.60 t of WFS is generated [13]. Table 1 shows the WFS production in different countries according to various authors [14–17].

In the literature researched, it has been observed that the name of the residue is presented in diverse forms, such as FS, as previously mentioned, used foundry sand (UFS) [18], spent foundry sand (SFS) [19], and WFS [20]. The authors of this paper will, henceforth, use the term WFS to refer to this material. The present systematic review will show, in the first part, the physical and chemical characteristics of WFS. In the second part, the fresh and hardened characteristics of three cement-based materials with WFS, namely, mortars, concrete, and SCC will be discussed. Then, in the third part, their technical-economic viability, together with the findings encountered in the literature examined, will be analyzed. In the fourth part, the challenges regarding the use of WFS in concrete will be listed. Finally, in the last part, a series of conclusions will be drawn.

Table 1
WFS production in different countries.

Country	WFS production (Mt)
China	48.75
India	11.49
United States of America	11.30
Brazil	3.00
South Africa	1.00
Spain	1.00
Poland	0.70

1.1. Types of WFS

The main component of WFS is silica sand (SS). SS is the most used sand in the foundry process because it is readily available and has a lower price compared to other types of sands that can be used. To improve the compaction of SS when making mold boxes, binders are often used to help maintain their shape and stiffness. The choice of these binders will depend on the size of the part and the alloy being used [21]. Additionally, the classification of WFS will depend on the type of binder used [22].

Green waste foundry sand (GWFS) is the most widely used option. The most common choice of binder is bentonite clay, to which a carbonaceous additive is added to support heat resistance and improve the cast surface [23]. Due to the previously mentioned additive, GWFS obtains a dark color (Fig. 2a). Chemical waste foundry sand (CWFS) consists mainly of silica, roughly 93% and 99%, in addition to about 1–3% chemical additives such as furfuryl alcohol, sodium silicates, phenolic urethanes, and phenolic formaldehyde [24–27]. CWFS is

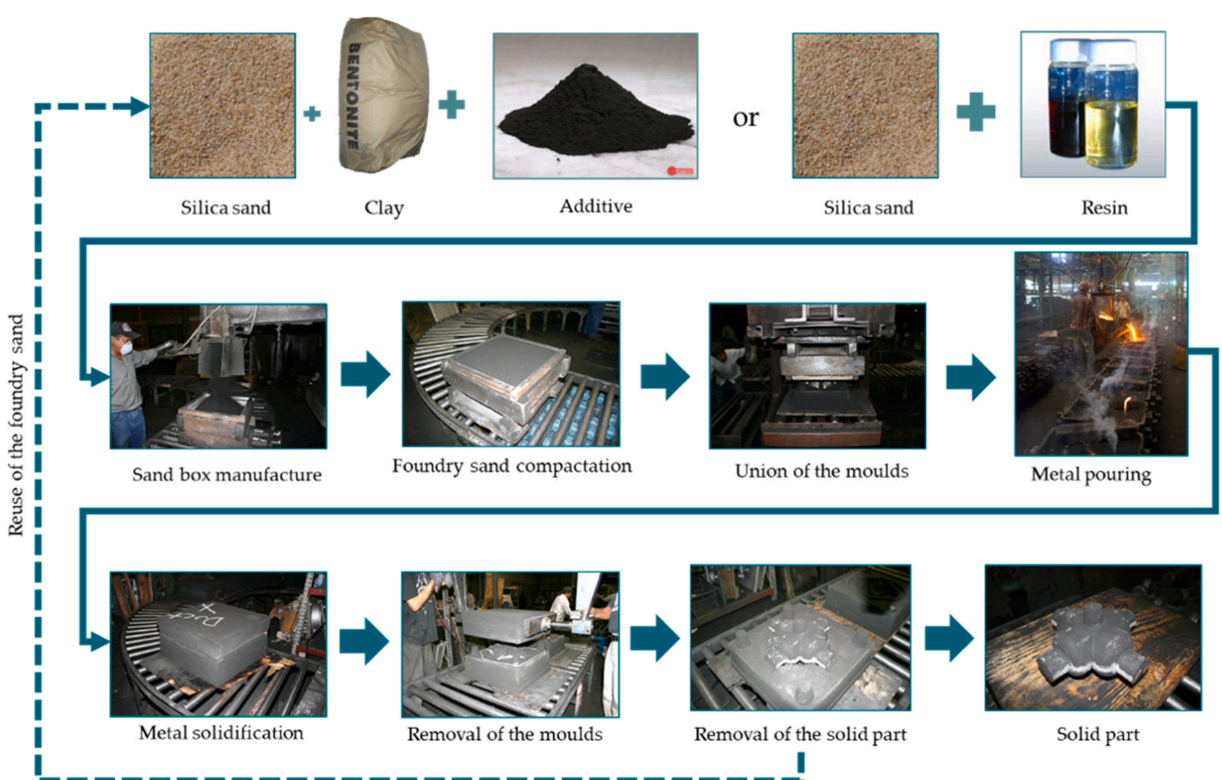

Fig. 1. Metal casting process (images under CC by 3.0).

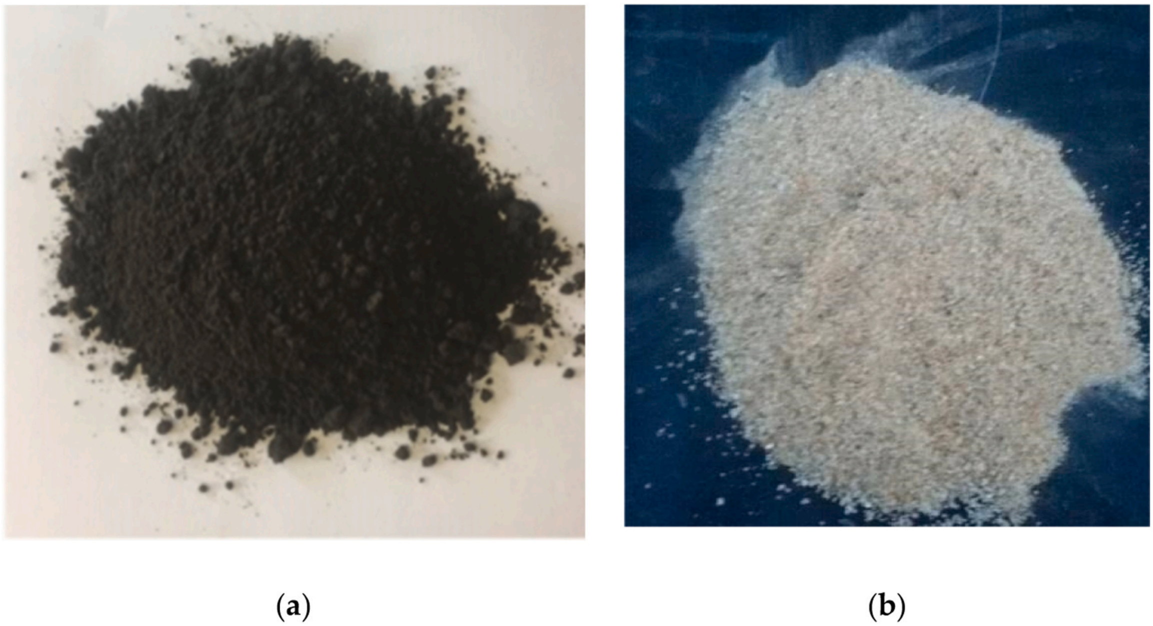

Fig. 2. GWFS (a). Source: [29] and CWFS (b). Source: [30].

off-white or medium tan in color (Fig. 2b). Chemical bonding systems are commonly used to manufacture cores and molds for nonferrous castings [28]. It is important to note that the colors of the two types of WFS may vary depending on the type and quantity of the additives and the casting process used.

1.2. *Physical-chemical properties*

The physical properties of WFS depend on variables such as: the type of foundry process implemented, the type and amount of additives used for molding, the number of times the sand has been reused, the industry sector making use of it, the differences in sand shape, as well as the fines content and mineralogy [31–34]. Regarding the particle size distribution, Iloh et al. [35] reported that the WFS from South Africa had a relatively uniform PSD, ranging between 0.15 and 0.60 mm, which is in concordance with the findings in the source literature [33]. Additionally, Dayton et al. [19] analyzed the WFS of 39 foundries in the United States, reporting that the dominant size fractions found ranged between 0.05 and 2 mm.

Fig. 3 shows the PSD of different types of WFS [7,30,35–38] along with the ASTM C-33 and EN standard particle size limits documented by diverse authors. It can be observed that the PSD of the WFS is, in most cases, within the upper and lower ranges of the EN and ASTM standards for particle sizes between 0.01 and 0.6 mm. In the cases where the WFS is above these ranges, it may be so because the size of the WFS varies according to the process implemented and the number of times it was recycled, as well as the type of binder used, which can increase the size and quantity of the fine particles involved/resulting. This matches the findings reported by Bilal et al. [39] inasmuch as when the sand is used in the foundry process, its morphology changes, as stated by Paul et al. [40].

As for its physical properties (density, absorption, and fineness modulus) Table 2 shows the results reported in the literature analyzed. It can be observed that regardless of the type of WFS, density can vary, with CWFS ranging from 2.34 to 2.80 g/cm^3, while GWFS varies from 2.24 to 2.63 g/cm^3. It has been reported that such variation in density is

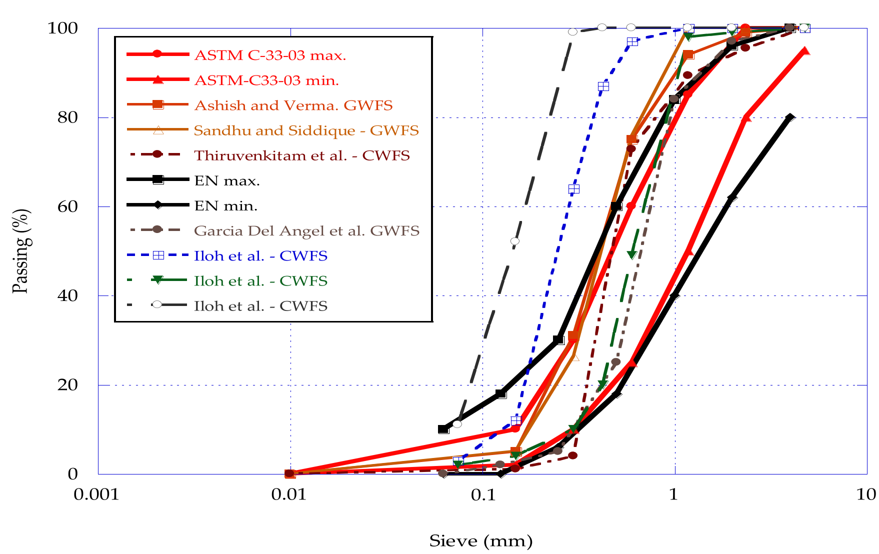

Fig. 3. WFS particle distribution according to different works.

Table 2
Physical properties of WFS according to different authors.

Reference	Type	Density (g/cm^3)	Absorption (%)	Fineness modulus
[35]	CWFS	2.60	-	1.40
	CWFS	2.60	-	3.20
	CWFS	2.80	-	0.50
[20]	CWFS	2.36	0.90	-
[40]	CWFS	2.69	0.48	1.60
[42]	CWFS	2.56	0.33	-
[43]	CWFS	2.34	0.75	-
[11]	GWFS	2.45	-	-
[35]	GWFS	2.50	-	1.20
[42]	GWFS	2.29	7.67	-
[44]	GWFS	2.63	1.01	0.51
[45]	GWFS	2.60	-	-
[46]	GWFS	2.24	1.13	-
[47]	GWFS	2.45	1.20	2.40

attributed to the fines and additives of the sand [41]. It can be observed that the absorption reported is less than 1% for CWFS, which could be attributed to the chemical binder not having absorbing properties, and for GWFS, the absorption level can reach up to 7.67%, which may occur due to the use of bentonite clay.

Regarding its chemical properties, these depend on the type of molten metal, the binder, and the additives used [48,49]. As can be seen in Table 3, its main component is silica dioxide (SiO_2), whose range varies between 84.00% and 98.59% in CWFS, while in GWFS it ranges from 85.40% to 94.41%. Regarding the aluminum oxide (Al_2O_3) content, it is observed that, in CWFS, this value is a little higher than 3%, while in GWFS, this value varies from 3.40% to 11.80%. The content of iron oxide (Fe_2O_3) in CWFS is up 3.60%, while in GWFS, this value is 1.82%.

During the valorization process of WFS, leaching is a major concern owing to the presence of organic and inorganic contaminants in the binder system. However, the foundry process that uses clay-type binders has a lower potential for leaching of organic compounds compared to chemically bonded systems [24]. Various metallic elements are present in the WFS, as reported by Miguel et al. [25] who analyzed different WFS samples and found high concentrations of Co and Pb, which is attributed to the sand binder being alkyd urethane. However, concentrations of Cr, Mo, Ni, and Ti are bound in the silica matrix, hence they do not pose a problem [25].

1.3. Microstructure

The microstructure of WFS is a highly significant parameter in the analysis of cement-based materials produced with it. This ensues because the microstructure, as revealed through scanning electron microscope (SEM) images at varying magnifications, assists in clarifying the mechanical and durability properties that are not discernible at a macroscopic level. According to Paul et al. [40], CWFS contains traces of Cr, Fe, and Al. Additionally, it was reported that the CWFS contains elements with higher atomic weight (white) in comparison to the SS particles (grey) (Fig. 4). From Fig. 4, it can be observed that the particle size of CWFS is more uniform and finer than the SS, with sub-angular and some rounded shapes being observed. Also, the distribution in the concrete mix is much more uniform compared to the SS. In the same study [40] it was reported that the CWFS contains silica and chromite quartz.

de Paiva et al. [43] studied CWFS with low (WFSPS1) and high (WFSPS2) traces of phenolic resin. In addition, the WFSPS2 was treated with a solution of 1.0 mol.L^{-1} of sodium hydroxide (NaOH) for 24 h (WFSP2T) to decrease its phenolic content. As can be observed in Fig. 5, EDS analysis of all the samples revealed traces of oxygen, carbon, and silica, consistent with findings by Iloh et al. [35] and Sgarlata et al. [54]. Moreover, the WFSPS1 samples showed fewer traces of phenolic resin attached to the sand surface (red lines), meanwhile the WFSPS2 and WFSP2T exhibited rougher surfaces fully coated with phenolic resin. This demonstrates that the NaOH treatment did not affect the WFSPS2 resin content. Furthermore, from Fig. 5, it can be observed that the CWFS has a sub-angular and round shape with finer particles than those of the SS, similar to Fig. 4. The presence of finer CWFS particles was expected due to changes in granulometry caused by the high temperatures of the casting process.

Regarding GWFS, Martins et al. [44] and Mushtaq et al.[55] reported that GWFS have a sub-angular to rounded morphology (Fig. 6), which is consistent with findings by other authors [37]. Similar to CWFS, the particle size is exceptionally uniform; in the case of GWFS, the size of such particles ranges between 200 and 500 μm. Iloh et al. [35] reported that the sea coal/bentonite coating was likely disturbed by sand grain abrasion during sand recovery and mold breaking (Fig. 7a). Additionally, Mushtaq et al. [55] reported that GWFS has coatings of loose material in the form of burnt carbon (Fig. 7b) and that GWFS contain quartz of silica, which is also consistent with findings reported by Sandhu and Siddique et. al. [56] (Fig. 7c). Fig. 7, as previously mentioned, shows the size of the particles to be around 200 μm. It can also be stated that the burnt binder results in the GWFS' rougher texture compared to that of

Table 3
Chemical composition of WFS according to different authors.

	WFS type						
Constituent	CWFS [40]	CWFS [42]	CWFS [43]	GWFS [50]	GWFS [51]	GWFS [52]	GWFS [53]
SiO_2	84.00	95.10	98.59	85.40	84.15	81.85	94.41
Al_2O_3	3.10	1.47	-	3.64	11.82	10.41	3.41
Fe_2O_3	3.60	-	0.42	1.45	1.53	1.82	0.58
SO_3	-	0.03	0.66	-	0.45	0.84	-
CaO	0.30	0.19	0.15	0.49	1.51	1.21	0.09
Na_2O	-	0.26	-	0.48	-	0.76	0.10
K_2O	0.40	0.68	0.06	0.38	0.29	0.49	0.45
MnO	-	-	-	0.03	-	-	0.01
TiO_2	0.10	0.04	0.06	0.16	0.26	-	0.03
P_2O_3	-	0.02	-	0.06	-	-	
MgO	-	0.19	-	0.66	-	1.97	0.05
Cr_2O_3	4.60	0.21	-	-	-	0.025	
NiO	0.30	-	-	-	-	0.005	
ZnO	-	-	-	-	-	0.018	
SrO	-	-	-	-	-	0.005	
Cl	-	-	-	-	-	0.071	
LOI	1.60	1.32	-	6.87	-	6.93	0.79

LOI: Loss on ignition.

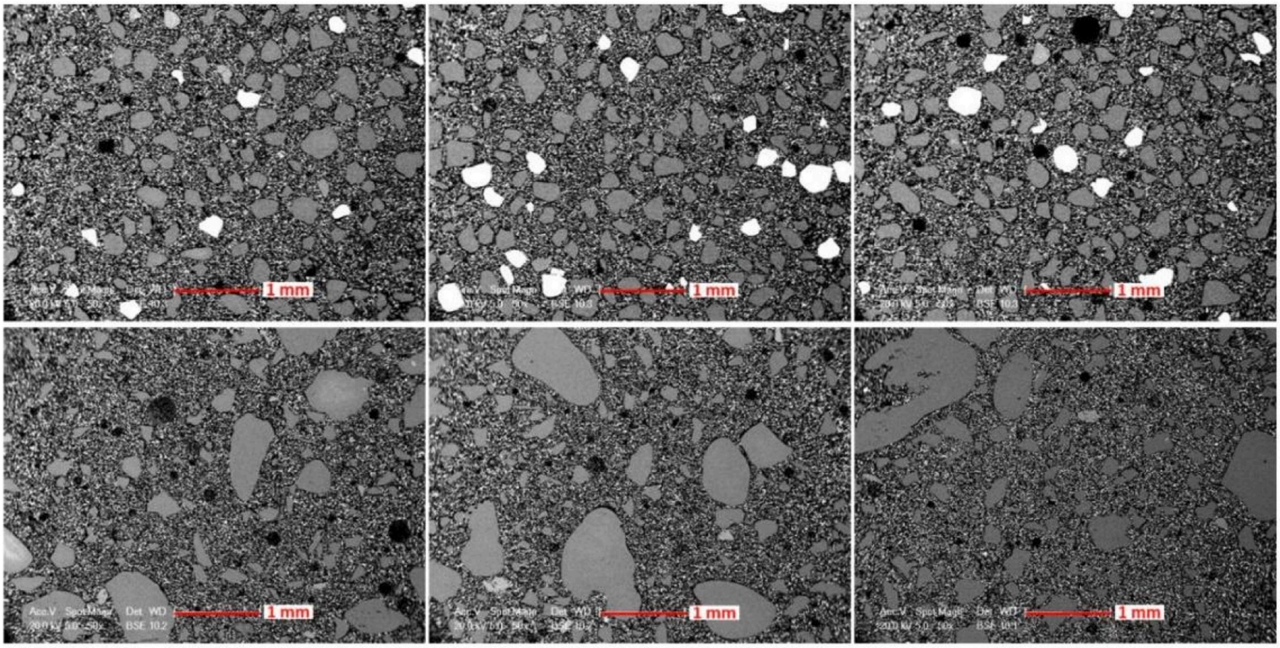

Fig. 4. SEM image of CWFS (upper row) and silica sand (lower row). Source: [40].

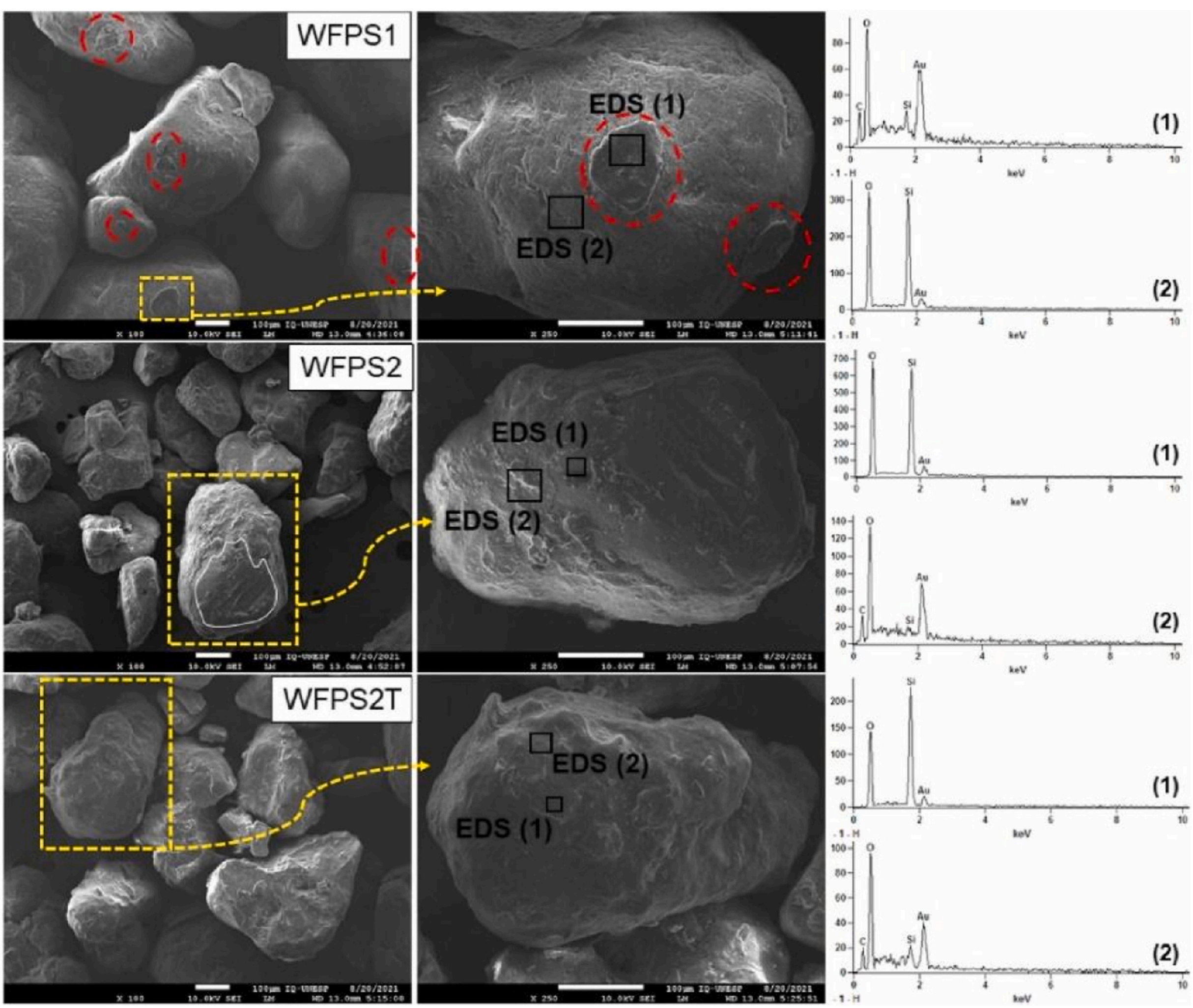

Fig. 5. SEM and EDS of CWFS. Source: [43].

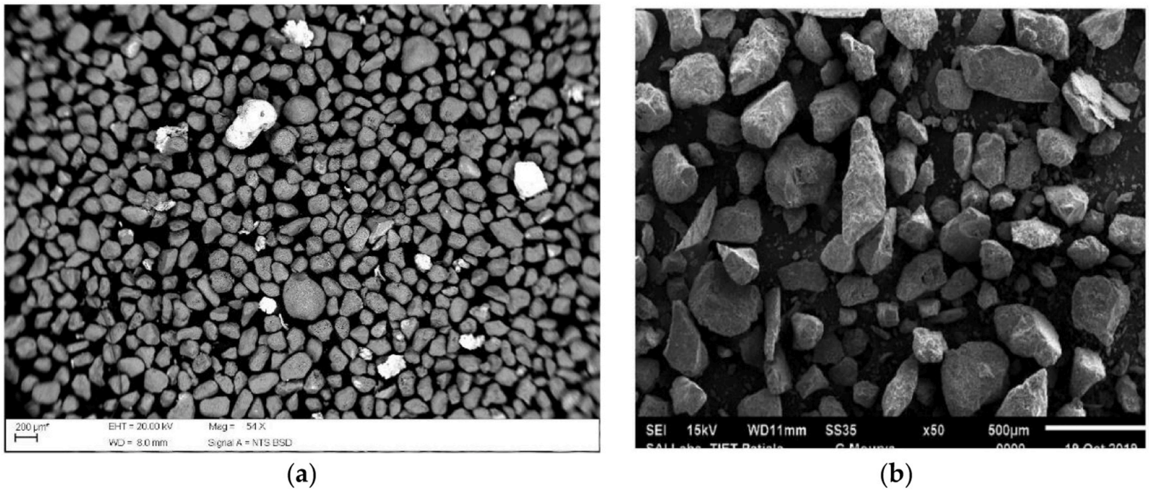

Fig. 6. SEM image of GWFS morphology. Source: (**a**) [44] and (**b**) [55].

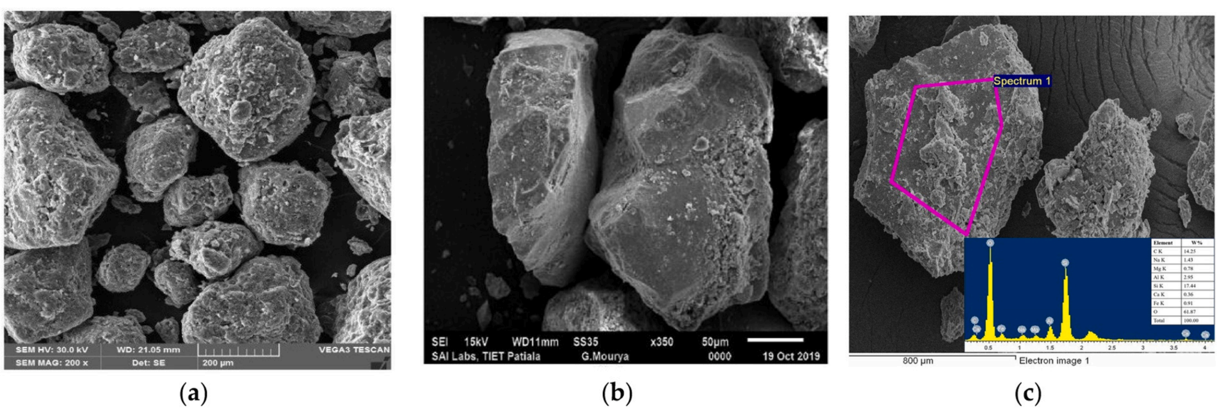

Fig. 7. SEM images of GWFS surfaces. Source: (**a**) [35], (**b**) [55] and (**c**) [56].

the CWFS.

As observed in the previous figures, both GWFS and CWFS microstructures contain traces of binder layers. These binder residues are the cause of the loss of workability and strength, as reported by other studies [1,57]. To counteract the adverse effects of WFS, various treatments such as water washing [58] and acid treatments [59] have been applied, obtaining favorable results by reducing the amount of impurities within the WFS.

2. Mortars made with WFS

Mortar is a blend of cement, sand, and water which is extensively used in the field of construction. Its primary purpose is to bind building blocks and create an even and stable surface between them. Mortar is also utilized for various finishing jobs such as plastering and filling gaps in walls, as well as for the repair and restoration of masonry structures. The properties of mortar can be altered by using different types of cement and aggregates [60,61], making it a versatile and adaptable material for various construction needs. Due to its strength and versatility, mortar is an essential component of the construction industry. Likewise, it is used in a diverse range of applications.

2.1. Physical properties

The physical properties of mortars are influenced by various factors such as the type of aggregate, the water/cement ratio (w/c), and the amount of cement used. Commonly evaluated physical properties include density (g/cm^3), porosity (%), and absorption (%). Although the physical properties of mortars may vary according to the materials and the mixing process selected, data from various authors [62–65] on the physical properties of mortars with a w/c ratio of 0.50 reported that their density ranges between 1.95 and 2.49 g/cm^3, while their porosity and their absorption varies from 3.30% to 18% and from 5% to 7.80% respectively. Typically, mortars made with a high w/c ratio tend to have lower densities, higher porosity, in addition to higher absorption.

Regarding mortars made with WFS, it has been reported that the inclusion of WFS decreases the density of the material because a higher replacement of WFS increases the w/c ratio [65]. The loss of density due to the high w/c ratio occurs because water within the cement matrix creates spaces between its particles, making it less compact and, therefore, less dense. Additionally, the density of the WFS can vary in relation to the NS used, which can also decrease the density of the mortar in cases where the NS is denser and a higher amount of WFS replacement is used. This higher w/c ratio also exerts its influence on its porosity along with its absorption, resulting in higher values than those associated with the reference mortar [65].

Similar to density, an elevated w/c ratio amplifies the presence of pores in the cement matrix. Surplus water leads to a rise in pore quantity and interconnection, altering both mechanical and durability properties. Additionally, the mortar's water absorption rises proportionally with an increased w/c ratio. Excess water opens more pores, making them susceptible to water absorption, thereby adversely affecting the durability of the mortar. In contrast, Khanduri [66] reported that the porosity of the mortars (w/c = 0.54) with up to 100% replacement of WFS decreased around 37%. This could be due to the fine particles of the WFS, which fill the micropores of the mortar matrix. The variation in the results may be a result of the high variability of the WFS' physical properties (density, absorption and fineness modulus) as well as its binder type (Table 2), and whether or not it has undergone treatment to remove impurities within the WFS.

2.2. Fresh state properties

Several studies have delved into the use of WFS in mortars, yielding varying results. Monosi et al. [49] found that as the percentage of WFS substitution increased from 10% to 30%, the workability of mortars decreased. Zanelato et al. [67] reported that the workability of mortars with 10–20% WFS decreased by about 3% compared to the control mortar. de Paiva et al. [43] investigated three types of WFS: one with low phenolic resin content, one with high phenolic resin content, and one alkaline-treated WFS. It was found that all WFS types reduced workability due to their high levels of absorption, a similar conclusion was reported [65] when replacing WFS up to 100% with different w/c ratios. Matos et al. [68] reported that partial and total replacement (50% and 100%, respectively) of NS with WFS reduced mortar workability due to the presence of bentonite and pulverized carbon particles in the WFS, which increased water absorption. The use of WFS in mortars requires careful consideration of the specific properties of the WFS and its potential impact on the final product.

The loss of workability is caused by inadequate particle size and shape. As previously mentioned, the majority of WFS particles are sub-angular, which can lead to interlocking between particles, thereby making the mortar less workable. Additionally, the presence of ashes and clay-like particles in the mix acts as a water absorbent. This is due to the high surface area of clay particles, which are often hydrophilic, leading to an increase in water demand [61]. Fig. 8 summarizes both the findings in the literature reviewed [43,49,65,68] and the fitting equations of the results published, it is observed that there is a linear relationship between the slump diameter decrease and the incorporation of WFS.

2.3. Mechanical properties

Mortars with WFS require high w/c ratios to mix properly, resulting in higher porosity and lower compressive strength [61]. This is attributed to the high absorption of WFS compared to NS, which is caused by impurities present in the WFS particles, as mentioned above. Such a high absorption level increases the porosity of the mortar, resulting in a less compact and therefore less resistant matrix. However, Cevik et al. [48] reported that 15–30% WFS substitution did not significantly affect compressive strength at 28 days. Zanelato et al. [67] found that mortars with 10–20% WFS showed increased flexural and compressive strengths compared to the control mortar, especially with 10% WFS. In both cases, the particle size of WFS varies from 200 to 500 μm, which is finer than NS.

The finer WFS particles fill the pores of the mortar matrix, creating a more compact and dense material, thereby increasing its flexural and compressive strength. de Paiva et al. [43] examined two types of WFS, one with low phenolic resin content and one with high content. Both types reduced the flexural and compressive strength due to the presence of resin films on the surface of the WFS, consistent with conclusions by [65]. As mentioned in the microstructure section, binder residues in the WFS particles cause the loss of workability because of absorption. This loss of workability leads to a less resistant structure, potentially explaining the losses in flexural and compressive strength.

Feijoo et al. [69] reported a 10% decrease in compressive strength when up to 25% of WFS was used. This loss of compressive strength was attributed to WFS absorption, excess of fine particles on aggregates'

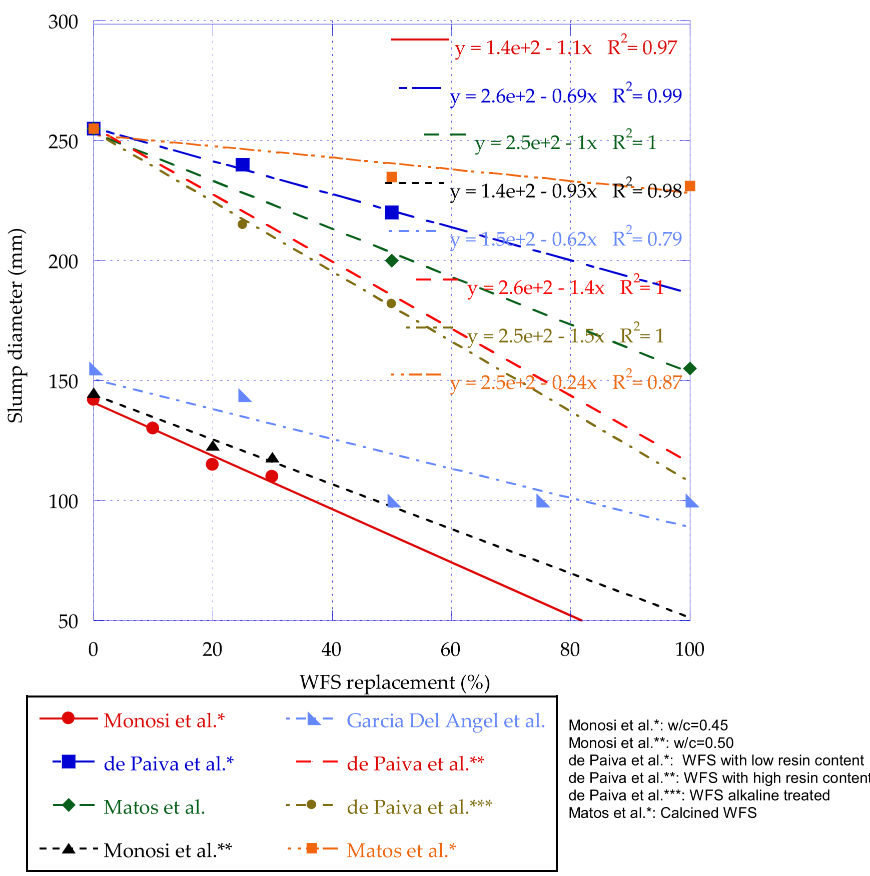

Fig. 8. Effect of the WFS incorporation in the workability of mortars according to different authors.

surfaces, and the presence of metallic elements such as iron, aluminum, and chromium whose hardness on the Mohs scale is lower than that of silica [40]. Fig. 9 summarizes the literature findings together with fitting equations, demonstrating a linear relationship between decreased compressive strength and higher WFS replacements. The observed linear correlation underscores the need for careful balance in WFS incorporation into mortars. Higher WFS replacements may compromise mortar structural integrity, therefore limiting load-bearing capacity. Adjustments in mix proportions, such as cementitious material amount, w/c ratio, and supplementary cementitious material use, are necessary to mitigate negative impacts.

A well-optimized mix design is essential to achieve a balance between sustainability goals and structural performance in mortars. WFS mortars find applications in various construction scenarios, including masonry work and repair applications. While they offer enhanced sustainability with WFS incorporation, potential compressive strength decreases must be considered when making informed decisions on load-bearing structure use. Balancing these factors is crucial for creating sustainable and structurally sound mortar structures in applications prioritizing durability and environmental considerations.

3. Durability

3.1. Effective porosity

Effective porosity in mortars is the ratio of interconnected voids within the material to its total volume, capable of holding air, water, or fluids. This influences their mechanical properties, durability, and performance. Similar to concrete, it gauges resistance against moisture, freeze-thaw cycles, chemicals, and degradation. Mortars with lower effective porosity show better resistance, enhancing longevity and reliability of structures. Feijoo et al. [69] reported that the inclusion of up to 25% of WFS increased capillary suction by 7% compared to the control mortar. Although this effect is reduced to 5% when the WFS undergoes a washing treatment (WFSW), separating the bentonite clay particles. Increased capillary suction and effective porosity in mortars incorporating WFS can lead to increased vulnerability to environmental factors such as moisture, freeze-thaw cycles and chemical attacks, therefore compromising long-term durability.

Increased capillary suction indicates a surge of interconnected voids within the mortar, which influences the overall porosity. A 5% reduction in capillary suction after the washout treatment suggests a better removal of binder residues and a decrease in interconnected pores, which could improve the mortar's resistance to environmental factors. It has also been reported that WFS subjected to thermal treatment (WFST) increased mortar porosity by 50% (Fig. 10). The increased porosity of the WFST may be attributed to the heat treatment not being as effective as the washing one, leaving traces of clay which absorb water from the mix, thereby creating an open system of pores.

3.2. Abrasion resistance

Mortars are commonly used in construction for applications such as coatings, finishes, and repairs. These mortar surfaces can be exposed to various abrasive elements, including foot traffic, vehicular movement, or the impact of solid particles carried by wind or water. Higher abrasion resistance in mortars is desirable because it ensures that the surface remains durable and maintains its aesthetic qualities over time. García Del Angel et al. [65] analyzed the abrasion resistance of mortars with WFS in different substitution percentages (Fig. 11). It was reported that increasing WFS replacement decreases mortar's mechanical durability due to the higher w/c needed to maintain workability. As stated, the binder particles within the WFS increase the water demand, leading to an increase of the w/c ratio, thus creating a more porous matrix and surface. This results in a more porous material, potentially leading to the loss of the bond between aggregates and cement [65]. Furthermore, the wear marks are in line with the EN-1338 standard [70], which indicates that the limit mark is 20 mm.

3.3. Sulphate attack

Sulphate attack is a common concern in construction, especially in environments where soils, groundwater, or other sources contain significant amounts of sulphates. It can result in various detrimental effects on mortars, including reduced strength, increased permeability, cracking, and overall degradation of the material's mechanical

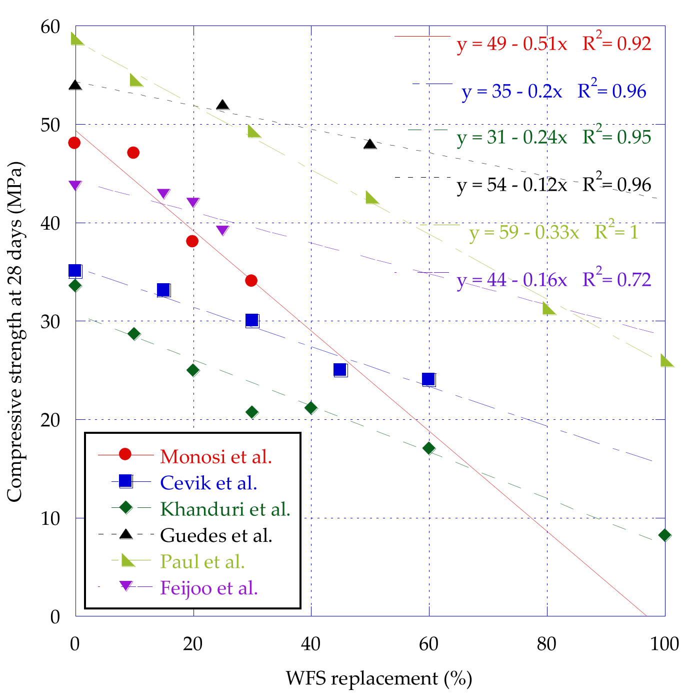

Fig. 9. Compressive strength at 28 days according to different authors.

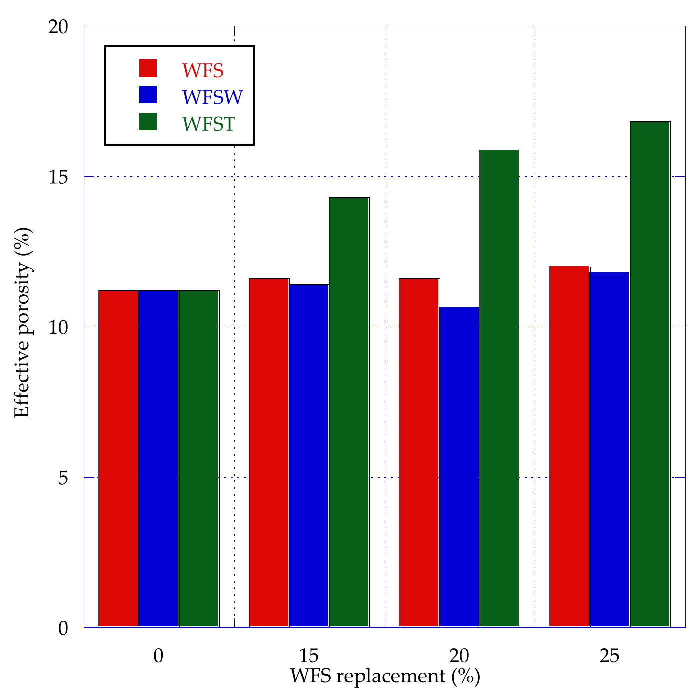

Fig. 10. Effective porosity of the mortars (control, WFS, WFSW, and WFST). Based on the results reported by Feijoo et al. [69].

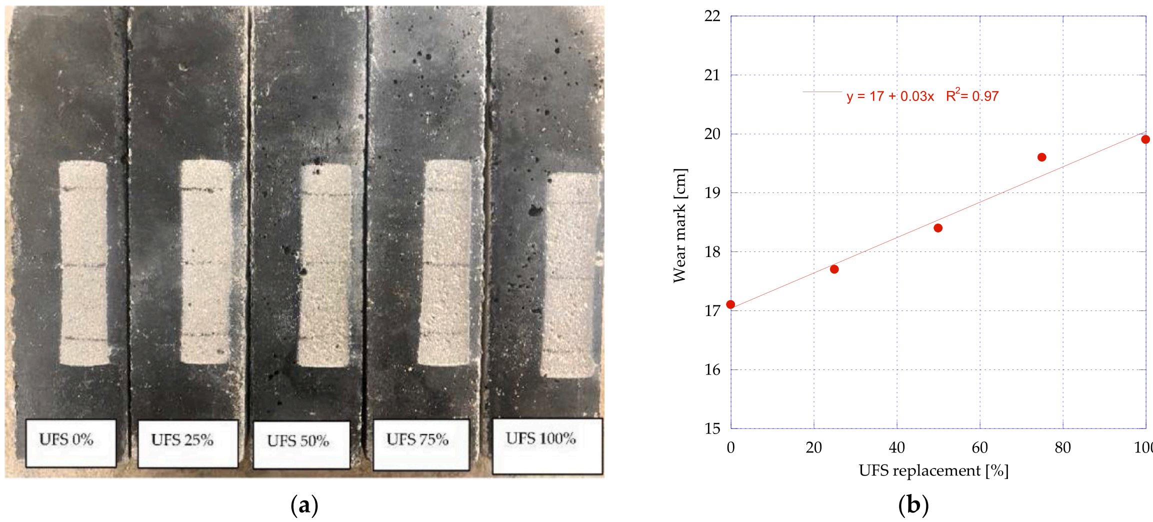

Fig. 11. mortars appearance (**a**) and wear resistance of mortars with WFS (**b**). Source: [65].

properties. Additionally, it can compromise the durability and longevity of structures, especially in environments where sulphate concentrations are high, such as in coastal regions or areas with sulphate-rich soils. In the study reported by Khanduri [66], the impact of the sulphate attack on mortars was examined, with varying amounts of WFS replacements up to 100%, at 28 and 90 days. The results indicated that the use of WFS led to a decrease in mass loss of the mortars incorporating up to 20% WFS.

However, further increases in the percentage of WFS used in the mortar resulted in an increase in mass loss, as depicted in Fig. 12. The decrease in mass loss with up to 20% WFS may be due to fine particles filling the pores of the cement matrix, consequently creating a more closed structure as reported by other authors [67]. However, when this percentage increases, losses in workability and compressive strength are to be expected due to a less dense and more porous structure [71,72]. This increases the effects of sulphate attacks caused by the formation of ettringite and gypsum, one such effect being the loss of mass [73].

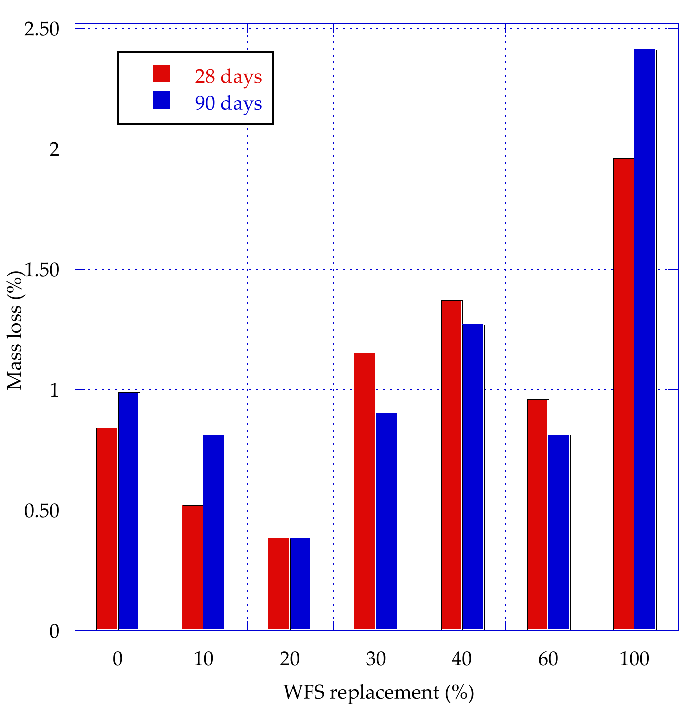

Fig. 12. Mass loss due the sulphate attack on mortars with WFS. Based on the data reported by [66].

4. Concrete made with WFS

Concrete is a widely used construction material that consists of cement, water, and aggregates. The type and size of aggregates utilized in concrete can markedly influence its properties. Commonly employed aggregates encompass crushed rock, gravel, and sand. In recent years, the utilization of recycled aggregates (RA) such as steel slags [74–79] coupled with construction and demolition wastes (CDW) [80–82] has gained importance. The selection of aggregates relies on considerations such as strength, durability, and environmental factors. Moreover, incorporating WFS in concrete aids in mitigating the environmental repercussions of waste disposal and conserving natural resources.

4.1. Physical properties

The physical properties of concretes depend on the characteristics of the aggregates and the w/c ratio. Typically, concrete density with natural aggregates ranges from 2.3 to 2.5 g/cm^3, with porosity falling between 9% and 10%. Information on the physical properties of WFS concrete in the hardened state is limited. It has been reported that the hard density for full WFS replacement is 2.46 g/cm^3, with porosity and absorption at 14.98% and 6.10% respectively [7]. Table 2 indicates that WFS is generally lighter than NS, potentially reducing overall concrete density. While advantageous for weight reduction in structures, it may alter the compressive strength of the concrete. Similar to mortars, WFS concrete could increase porosity, affecting permeability as well as resistance to water and other aggressive substances.

High porosity may result in increased absorption of water and chemical substances, impacting concrete durability over time. WFS concrete may exhibit higher water absorption due to the porous nature of WFS particles [83]. Excessive water absorption can reduce workability, warranting adjustments in mix design to maintain the desired properties. Additionally, increased absorption can affect concrete resistance to freeze-thaw cycles and chemical attack, which is critical for the durability of concrete structures.

Aggarwal and Siddique [84] reported that the fresh density of the concrete mix increased with the replacement of NS by a combination of WFS and bottom ash from 2.39 to 2.45 g/cm^3, thus representing an increase of around 2%. On the contrary, some authors have reported that the WFS decreased its fresh density, Ganesh et al. [85] reported that for a WFS replacement of up to 50%, hard density decreased from 2.39 (control mortar) to 2.31 g/cm^3, a decrease of around 3%. Ahmad et al.

[83] reported a decrease in fresh density, with the inclusion of up to 50% of WFS, of around 1.45% which is due to the lower density of the WFS used compared to NS, which was also observed in the results reported by Siddique et al. [86].

From Fig. 13, it can be observed that the fresh density of concretes with WFS varies with the replacement percentage, stabilizing at approximately 2.42 g/cm^3 when 20% WFS replacement is used. Increasing the substitution percentage, especially when WFS is combined with other admixtures (e.g., bottom ash), can give the concrete mix a higher fresh density. Conversely, the decrease in fresh density is attributed to the fineness and porosity of the WFS, which increases the water demand of such a concrete mix [83].

4.2. Fresh state properties

A critical indicator for assessing the fresh properties of concrete is the slump test. Siddique et al. [87] established an initial slump value of 90 mm for their control concrete mix. However, when substituting NS with WFS at rates of 10%, 20%, and 30% by weight, the slump values decreased, registering a decline from 85 mm to 80 mm. In another study reported by Naik et al. [88], where NS was substituted with WFS at rates of 25% and 35%, the slump values for WFS-containing mixes dropped significantly to 32 mm and 29 mm, respectively, compared to the control mix with a slump value of 152 mm. Guney et al. [11] reported an initial control mix with a slump value of 160 mm. When replacing NS with GWFS at rates of 5%, 10%, and 15%, the slump values decreased to 150 mm, 110 mm, and 60 mm, respectively. Khatib et al. [89] reported a systematic loss in workability as the WFS content percentage increased. This loss in workability was attributed to the increased fineness of the fine aggregate used.

Etxeberria et al. [90] reported varying slump values for concrete mixes with natural coarse aggregates and WFS, ranging from 150 mm (CWFS) to 750 mm (GWFS). The lower slump values were attributed to the presence of binders in WFS, which increased the water demand due to the use of components such as ashes, clay-type fine materials, and their impurities [31]. Monosi et al. [32] explored two types of WFS: one recovered directly from molds' disposal and the other from the aspiration process. A 20% decrease in the slump test was reported when using a 20% WFS replacement for NS in both cases, in contrast to a control concrete mix with a 160 mm slump [32]. Additionally, at a 30% replacement rate, WFS from the molds' disposal resulted in a 150 mm slump, while WFS from the aspiration process led to a slump of 120 mm, representing a decrease of 6.25% and 25%, respectively. This indicates that as the replacement rate increases, the finer particles in the WFS contribute to a decrease in workability [32].

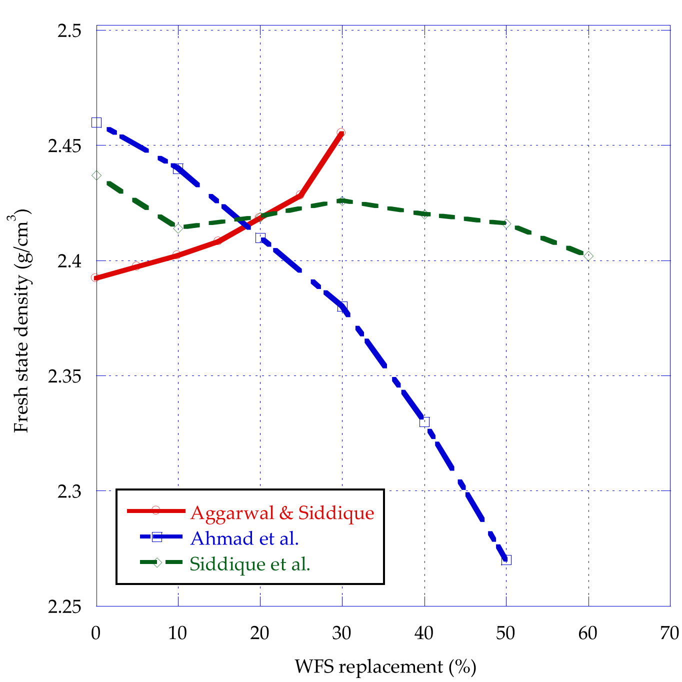

Fig. 13. Fresh density of concrete with WFS according to different authors.

Bilal et al. [39] examined the effects of up to 40% WFS replacement in concrete and noted a decrease in slump, attributing it to the finer particles in WFS, including clay-type materials, ashes, and their impurities, which increased water absorption. Mushtaq et al. [55] reported that incorporating WFS in concrete reduces workability, particularly at replacement rates of 30% or higher. This decrease in workability is likely due to WFS particles being finer and more uniformly graded than natural river sand particles, requiring more water for achieving the desired workability [55].

Fig. 14 presents the findings reported by the previously mentioned authors, along with their corresponding fitting equations, illustrating the correlation between slump reduction and the extent of WFS replacement. It can be observed that in all cases, there is a decrease in the workability of the concrete studied. However, such a decrease is less pronounced with replacements in the range of 5–10%. Therefore, the use of WFS in the manufacture of concrete is an alternative to the use of NS. The partial reduction of workability should be taken into account when deciding to work with this material.

Although in replacements within a range of 5–10% there is no significant change in the workability of concrete, those over 10% result in a loss of workability due to the presence of clay particles and chemical binders in the WFS. The presence of binders in the WFS particles increases the water demand of the mix, leading to greater water absorption and resulting in a loss of workability. The practical implications of the loss of workability in concrete when using WFS include possible complications with its placement and compaction, which can cause defects to appear on the surface and in the concrete matrix. This could be compensated by an increase in vibration energy, however this may raise personnel, equipment, and safety costs. These implications can be mitigated by an adequate mix design, specialized laboratory support, the use of superplasticizers and water-reducing additives.

4.3. Mechanical properties

The increase or decrease in compressive strength can vary depending on the substitution rate, the type of WFS used, the type of concrete being made, and whether there is a previous treatment. According to Siddique et al. [87], the increase in compressive strength can be attributed to several factors associated with the use of WFS compared to NS. These factors include the finer particles of the WFS used, their silica content, and a more compact concrete structure [87]. Silica in WFS often contains amorphous forms, which exhibit pozzolanic reactivity when in contact with calcium hydroxide produced during the cement hydration process This reaction results in the formation of additional calcium silicate hydrate (C-S-H) gel, contributing to a denser and more compact concrete structure [86]. The research consulted illustrates a significant enhancement in compressive strength when substituting sand with WFS, ranging from 10% to 30%, resulting in respective increases of 4%, 5%, and 10% [87].

Another study by Siddique et al. [86] indicates that substituting 30–50% of NS with WFS leads to compressive strength gains ranging from 2% to 5%. This was attributed to the fine particles of the WFS, which spread firmly throughout the mix, thus making the C-S-H gel equally well spread within the cement paste [86]. Martins et al. [91] have also documented noteworthy increases in compressive strength, ranging from 2% to 12%, when replacing 20–50% of NS with WFS. This increase in strength is attributed to the higher silica content in WFS and its fine, consistent grain shape [91], as well as the large formation of C-S-H gel as stated by Siddique et al. [86].

In the case of fungal treated WFS (FWFS), Kaur et al. [92] found that

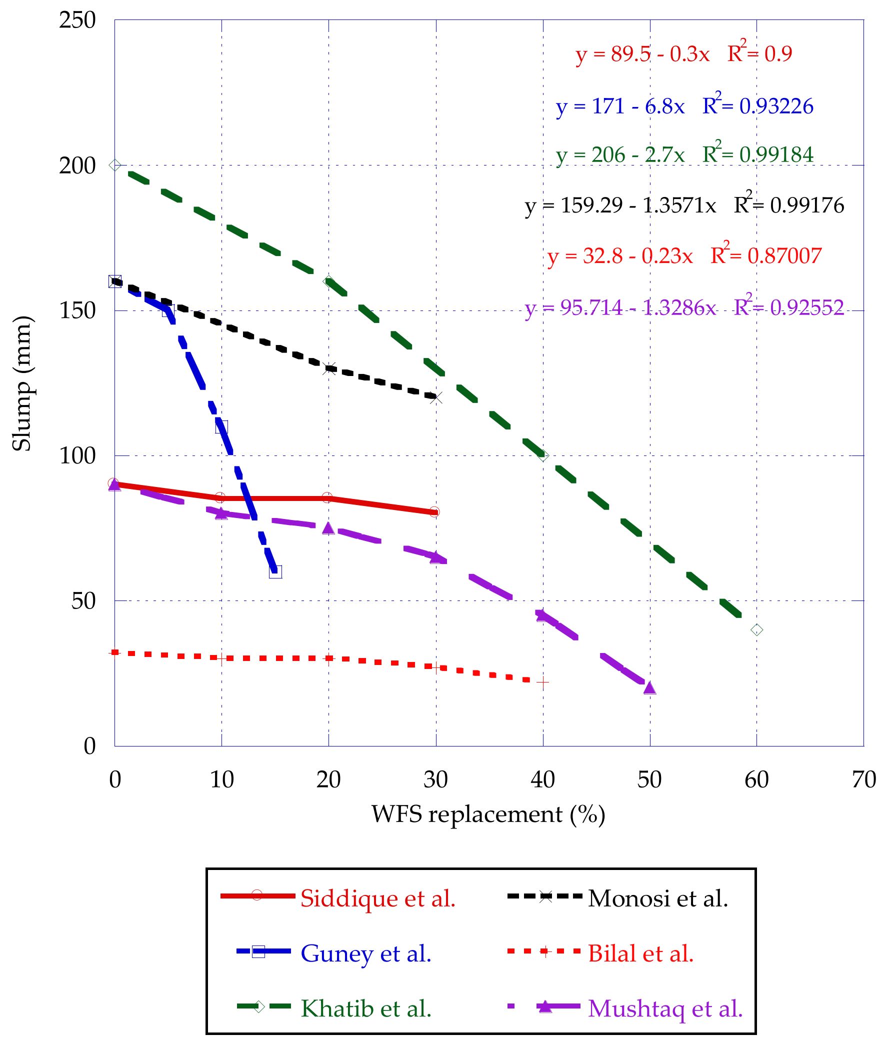

Fig. 14. Influence of the WFS replacement on the workability of concrete according to different authors.

substitutions of 10%, 15%, and 20% resulted in increased compressive strength. The most substantial enhancement, a remarkable 16% increase, was observed when 10% of NS was substituted with FWFS. Such strength improvement is attributable to microbially induced minerals formed by fungi, often referred to as calcified filaments [93], and biomineral structures derived from fungal activity, acting as filler materials, thereby reducing water absorption and porosity [92]. Furthermore, Bilal et al. [39] reported that concrete with up to a 30% replacement of WFS exhibited an increase in compressive strength ranging from 2.67% to 7.82%. This improvement was attributed to finer particles filling voids within the concrete, resulting in a denser matrix with reduced porosity [39], as stated by other authors [86].

In contrast, the reduction in compressive strength is attributed to various factors associated with WFS. One of the main reasons is the high surface area of WFS particles, which leads to a decrease in the water-cement gel within the matrix. The aforementioned high surface area increases the water demand of the concrete mix, causing an increase in the w/c ratio needed to maintain a certain level of workability. Additionally, impurities within the WFS, such as clay particles and ashes, may lead to poor bonding between aggregates and the cement paste, as documented by Gholampour et al. [47]. Moreover, this poor bonding could result in a weaker interfacial transition zone (ITZ), as reported by Naik et al. [88] which will potentially cause a decrease in compressive strength [88]. A similar conclusion is reached by Monosi et al. [94], who attribute the decrease in compressive strength to the presence of binders in WFS containing fine carbon and clay particles, which causes a delay in cement hydration in addition to a loss of contact and links between the cement paste and aggregates.

Several studies [86,91,95] have explored the substitution of 10% of NS with WFS in conventional concrete, revealing a decrease in compressive strength ranging from 3% to 14%. When the substitution rate increases to 20%, the decrease in compressive strength ranges from 7% to 16%, as reported by various authors [86,89,92,94–96]. The impact on compressive strength becomes more pronounced when 30% of NS is replaced by WFS, with resulting decreases ranging from 6% to 22%, as reported by Ganesh et al. [81], Basar & Deveci [52], and Monosi et al. [94]. Further substitution, such as 40% of NS with WFS, results in decreased compressive strength ranging from 11% to 28%, as documented by Ganesh et al. [96], Khatib et al. [89], and Basar & Deveci [52]. A 50% replacement of NS by WFS leads to a reduction in compressive strength of 24% and 28%, as reported by Ganesh et al. [96] and Gholampour et al. [47].

In fewer instances, where a 60% substitution of NS by WFS is explored, Siddique et al. [86] reported a decrease of 18% in compressive strength. Finally, a complete substitution of NS by WFS results in a substantial decrease in compressive strength, ranging from 40% to 62%, as reported by Khatib et al. [89] and Gholampour et al. [47]. The previously mentioned results, where the reduction in compressive strength increases with the substitution of WFS, may be due to factors such as the finer nature of WFS compared to NS, lower workability, a more porous concrete structure, and the presence of impurities in WFS. The practical implications of reduced compressive strength in WFS concrete encompass concerns for structural integrity, durability, and safety. The lower compressive strength may compromise the load-bearing capacity of concrete elements, potentially affecting critical infrastructures. To mitigate these challenges, it is recommended to optimize the mix design, incorporate supplementary cementitious materials, and use chemical admixtures.

Fig. 15 provides a summary of the findings from the literature analyzed, illustrating a consistent trend wherein WFS tends to reduce the compressive strength of concrete. It is observed that the higher replacement of WFS as a substitute for NS generates a loss of compressive strength in the majority of cases. It is important to note that the variability of the results may be due to the characteristics of each type of WFS used in each of the studies. However, in general, when using WFS in large amounts of substitution, a loss of compressive strength is to be expected.

4.4. *Durability*

4.4.1. *Carbonation depth*

Carbonation is a chemical process that occurs in concrete when CO_2 from the air reacts with the hydrated cement minerals. In this process, CO_2 dissolves in the pore water of the concrete mix and reacts with calcium hydroxide ($Ca(OH)_2$), a byproduct of cement hydration, forming calcium carbonate ($CaCO_3$) and water [97]. This reaction leads to the conversion of $Ca(OH)_2$ into $CaCO_3$, causing a reduction in the alkalinity of the concrete. One of the significant concerns associated with carbonation is its potential impact on reinforcing steel. The reduction in alkalinity resulting from carbonation can lead to a decrease in the passivity of the steel reinforcement process [98]. In a less alkaline environment, the protective oxide layer on the steel surface may break down, therefore making it more susceptible to corrosion.

Carbonation depth in concrete refers to the extent to which CO_2 from the air penetrates the material and reacts with its components. Siddique et al. [86] reported that the carbonation depth increases with age. The factors associated with this are the concentration of CO_2 in the environment, the relative humidity, additives, and concrete inhomogeneity [98]. Fig. 16 shows how the WFS incorporation increases the carbonation depth at 90 and 360 days. It can be observed that the carbonation depth increased with time. Nevertheless, the carbonation depth does not represent a risk for the steel bars, being the maximum value 2 mm and 5 mm at 90 and 360 days respectively. Ahmad et al. [99] reported similar results analyzing up to 50% WFS replacement at 90 and 180 days (Fig. 16). As in the previous case, it is observed that the carbonation depth increases with time. Despite increasing with a WFS replacement, there is no carbonation depth greater than 8 mm at 180 days. The increment in carbonation depth happened because of the low concrete workability, which was caused by a low compactness and resulted in a continuing porous system [83].

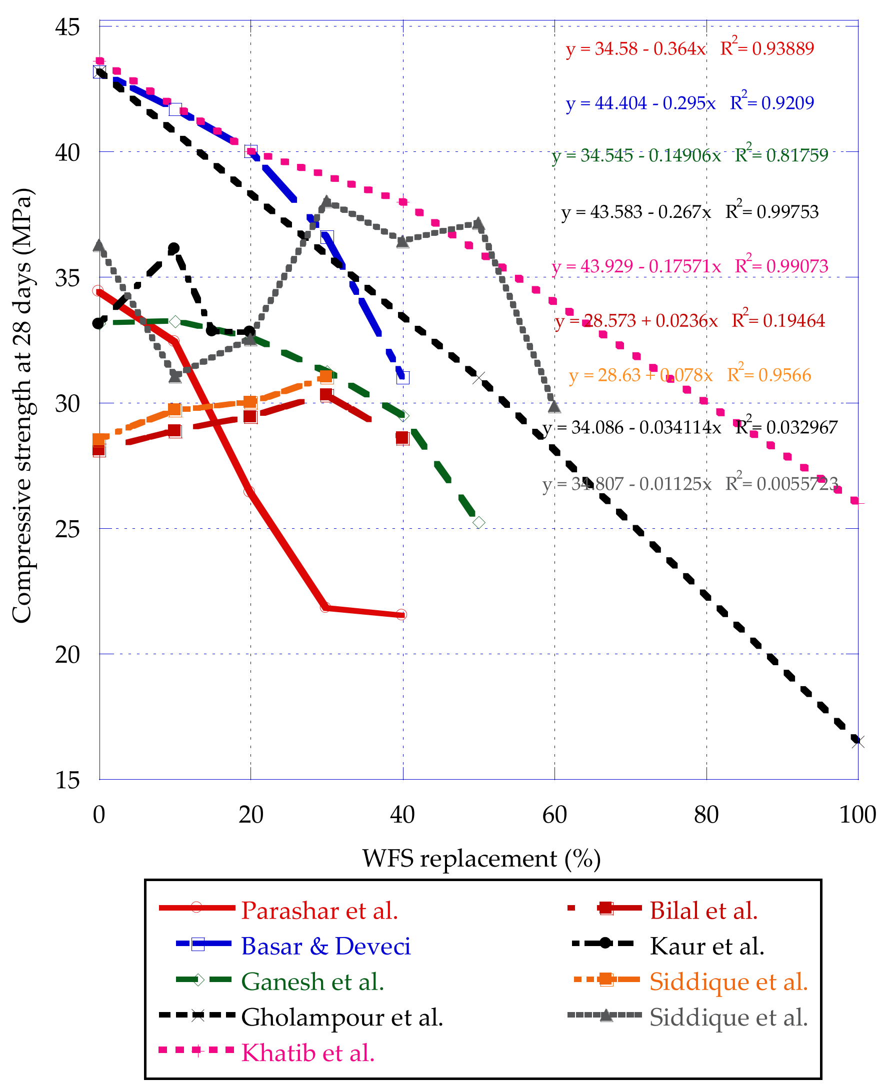

Fig. 15. Influence on the compressive strength with WFS according to different authors.

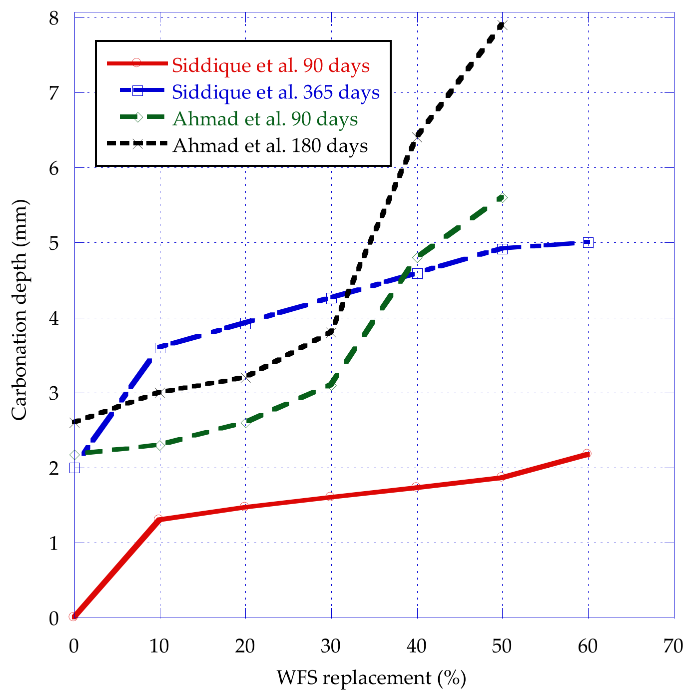

Fig. 16. Carbonation depth of concrete with WFS incorporation according to different authors.

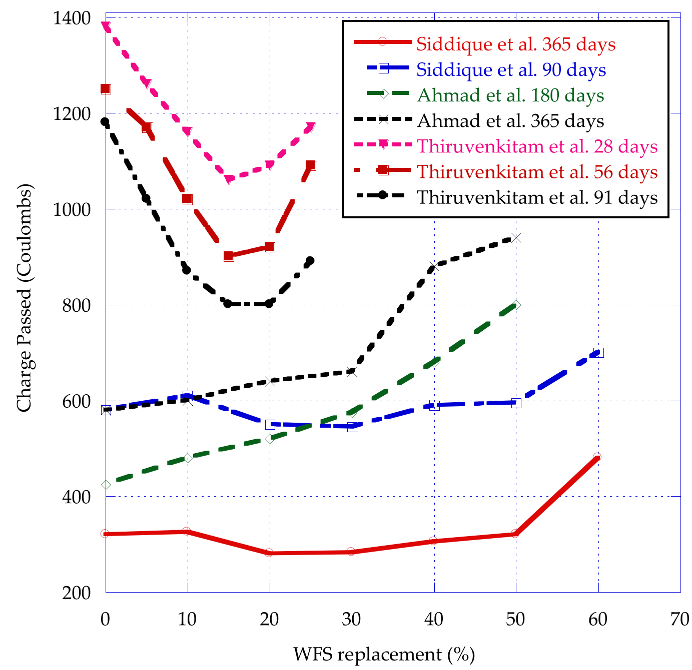

Fig. 17. Rapid chloride penetration values of concrete with WFS according to different authors.

From Fig. 16, it can be concluded that the integration of WFS (up to 60% replacement) into the concrete matrix does not exert adverse influences on the behavioral attributes pertaining to carbonation depth. Additionally, at high ages (up to 365 days), the carbonation depth manifested by concrete containing WFS registered measurements of less than 10 mm. These findings demonstrate that WFS can be used effectively as a NS replacement and can provide adequate protection to the steel reinforcement of reinforced concrete structures. To decrease the depth of carbonation when using WFS, the design of a low permeability concrete could be implemented, hence increasing the thickness of the concrete layer to ensure the presence of an adequate distance between the steel reinforcement and the concrete surface as well as the use of corrosion inhibitors.

4.4.2. Rapid chloride penetration

Exposure to chloride-rich surroundings diminishes the longevity of reinforced concrete structures. The corrosion of reinforcement, triggered by the infiltration of chloride ions, stands as a primary factor leading to the decay of reinforced concrete structures in coastal settings [100]. The Rapid Chloride Penetration (RCP) test is a critical method employed in assessing the durability of concrete structures, providing valuable insights into their resistance against chloride ion penetration. Chloride penetration is a significant factor contributing to the corrosion of reinforcing steel within concrete, which can lead to structural deterioration [101]. Siddique et al. [86] studied the RCP value of concrete with WFS up to 60% at 90 and 365 days. From Fig. 17, it can be seen that the RCP value decreases with age. At 90 days, the RCP value for the WFS concrete mixes was found to be higher than the control concrete except for concrete with 20 and 30% replacement. The maximum value was observed for the concrete with 60% WFS. The concrete mixes studied showed lower RCP values, indicating the good permeability of WFS concrete.

Thiruvenkitam et al. [30] reported that the inclusion of up to 20% WFS decreased the RCP at 25, 56, and 91 days. This is due to the filler effect of the WFS and the acceleration of cement hydration [30]. On the contrary, Ahmad et al. [83] reported that air pockets were created due to the presence of flour grains and wood grains in WFS, resulting in the creation of a continuous pore system that allows for the piercing of chloride ions (Fig. 17). Fig. 17 shows the variability in RCP test results in concrete. It can be observed that in most of the reported cases the RCP decreases with the majority of the WFS replacements and with age. However, in other cases an opposite effect may occur due to impurities in the WFS. In both cases, the charge that passed through the concrete is around 1000–2000 Coulombs, which classifies it as a concrete with low chloride ion permeability [100]. Although the chloride ion permeability is low, to improve these results and perhaps decrease the variability, an alternative is to pre-treat the WFS to decrease the amount of impurities and binder residues.

4.4.3. Ultrasonic Pulse Velocity

UPV is a non-destructive testing method widely used to assess the quality and integrity of concrete structures. Regarding UPV, Bilal et al. [39] reported that replacing NS with WFS up to 30% is optimal, but it should not exceed 40%. Adding WFS increases the rebound number and UPV, indicating improved quality, homogeneity, and impermeability of the concrete. This same WFS replacement was reported to be the optimal according to the findings of Reshma et al. [102]. A similar conclusion was stated by Thiruvenkitam et al. [30]. It was reported that increasing WFS content in concrete up to 15 wt% increases UPV. Beyond 15 wt%, UPV decreases, but it remains above the control mix, this is due to the entrapped air bubbles on the surface of WFS [30].

Siddique et al. [103] reported that in M20 and M30 types of concrete the UPV value increases as the quantity of WFS in concrete and the duration of time increases (from 28 to 365 days), resulting in a more compact internal structure. According to Bhardwaj and Kumar [31], an increase in UPV indicates improved density, homogeneity, and absence of defects in concrete. However, when WFS replacement levels exceeded 20%, there was a gradual decrease in UPV values. This may be possible because a higher WFS replacement decreases the workability of the concrete, creating a less dense structure with a more open pore network, which could explain the decrease in the UPV value. Nevertheless, the UPV values increase with the curing age [89]. Fig. 18 shows how the UPV value increases as a function of WFS replacement. The incorporation of 20–40% of WFS increases the UPV value which varies from 4048 to 4482 m/s, making it a denser, more uniform, and homogeneous

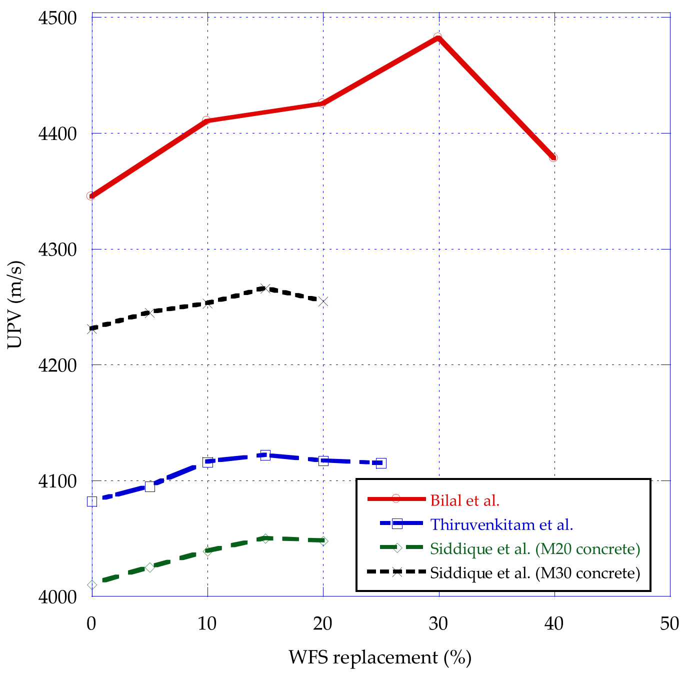

Fig. 18. Influence of WFS on concrete in UPV tests according to different authors.

material.

4.4.4. Freeze-thaw resistance

The alternating cycles of freezing and thawing induce internal stress within concrete, resulting in surface scaling, cracking, heightened permeability, reduced strength, corrosion of reinforcement, and overall performance deterioration. This highlights the significance of freeze-thaw resistance in safeguarding the durability of concrete structures. Regarding the loss of mass after freeze-thaw cycles, Naik et al. [104] studied the freeze-thaw resistance of bricks and paving stones containing 25% and 35% of WFS. The study found that partial substitution of fine aggregate with WFS decreased freeze-thaw durability. Paving stones exhibited 2.3 times higher freeze-thaw resistance than bricks due to their lower water-cementitious materials ratio. It was concluded that increasing WFS in bricks decreased freeze-thaw resistance, and significant mass loss occurred in paving stones due to surface spalling between 60 and 150 cycles [104].

Smarzewski and Barnat-Hunek [34] reported that the mass loss of concrete after 180 freeze-thaw cycles was two times higher with 5 and 15% WFS replacement compared to the control concrete. This may be due to the physical properties of the WFS concrete, in which the porosity and absorption of the WFS concrete is 10 and 12% higher (respectively) than the control concrete, which could lead to deterioration of the concrete after freeze-thaw cycles. Regarding the compressive strength after freeze-thaw cycles, Guney et al. [11], after 80 freeze-thaw cycles, reported that concrete with 10% WFS exhibited sufficient resistance to the freezing period. This is evident as concrete with up to a 15% replacement showed a reduction of 18% in compressive strength, whereas concrete with 10% WFS experienced a loss of less than 10% in compressive strength. This could be attributed to the formation of a denser structure in the concrete at 10% WFS replacement level compared to the concrete with 15% WFS. A similar explanation was reported by Aggarwal et al. [84] which attributed the poor performance of concrete with up to 30% of WFS and coal bottom ash to the non-formation of proper C–S–H gel as compared to the control mix microstructure.

4.4.5. Abrasion resistance

Among the various types of wear and tear that concrete structures endure; abrasion resistance is one of the most prevalent forms of deterioration [30]. According to Singh et al. [105], the abrasion resistance of concrete mixtures increased with the use of WFS as a replacement for fine aggregate, regardless of curing age. Concrete containing 0%, 5%, 10%, 15%, and 20% WFS had a depth of wear of 2.84 mm, 2.60 mm, 2.50 mm, 2.28 mm, and 2.40 mm, respectively, at 28 days of age. This trend was consistent at 91 and 365 days of curing, indicating that the depth of wear decreased with age for a given WFS content, which implies an increase in abrasion resistance. The decrease of the abrasion wear with the addition of WFS occurred because of the densification of the paste structure due to the fine particles of WFS [105]. Thiruvenkitam et al. [30] also reported that abrasion resistance improved with up to 20% of WFS, likely due to the presence of finer WFS particles with a higher hardness index [30]. Additionally, it has been reported that with 20% of WFS replacement, the density of the concrete is improved due to the densification of the ITZ and the presence of lesser porosity as reported by Manoharan et al. [106].

5. Self-compacting concrete made with WFS

SCC emerged as an alternative to reliance on workers during the reconstruction period after World War II [107]. It was developed in Japan in 1986 by Okamura, and the first prototype was presented by Ozawa two years later [108]. In 1994 the Japanese Society of Civil Engineers published the first guidance documents for its use. Over the years, state-of-the-art reports on SCC have been published by institutions such as RILEM and European project groups [109]. SCC reached America in the mid-1990 s and was used in rehabilitation projects and the precast industry [110]. SCC is renowned for its inherent ability to flow effortlessly and fill formwork under its own weight, without requiring external consolidation methods such as vibration. Noteworthy characteristics of SCC include its exceptional workability, superior flowability, resistance to segregation, and self-leveling and compacting capabilities. These unique attributes have positioned SCC as a promising material in construction, offering advantages such as enhanced durability, superior surface finish, and reduced labor demands during implementation.

SCC is typically made with fine materials such as fly ash (FA) and silica fume (SF), along with superplasticizers to achieve the desired flow properties. The use of FA and SF in the production of SCC enhances workability, compressive strength, and durability, while also improving impermeability, resulting in more durable concrete. Additionally, the use of these fine materials is cheaper than conventional cement, thereby reducing cement production and leading to lower CO_2 emissions in the environment [111]. Superplasticizers are essential in SCC for achieving desired flow properties. They reduce the w/c ratio while maintaining workability [112]. By dispersing cement particles efficiently, superplasticizers enhance fluidity, allowing SCC to flow and fill formwork under its weight. This ensures a uniform distribution of the components, preventing segregation and enabling optimal self-leveling and compacting properties in SCC [113].

SCC finds diverse applications across construction sectors, including buildings [114,115], bridges [116–118], and infrastructure projects [119,120]. Its versatility stems from its exceptional flow properties, which enable effortless filling of formwork without external consolidation. This makes SCC particularly suitable for intricate structures and congested reinforcement layouts. Moreover, SCC offers advantages such as enhanced construction efficiency and durability compared to traditional concrete [121]. Its ability to self-level and compact reduces labor requirements, speeds up construction, and ensures high-quality finishes. [122].

The increasing exploitation of raw materials for the construction industry due to the growth of infrastructure has led researchers to focus their attention on alternative materials. The use of RA has been studied and documented, proving the feasibility of CDW [123]. It has been reported that SCC with RA from railway structures meets the EFNARC [112], EN-206–1 [124], as well as durability standards in terms of wear resistance, permeability, and water penetration [125]. SCC with RA from precast elements showed slightly lower mechanical properties than control concrete [126]. However, the fresh properties with RA met the EFNARC requirements [112]. Regarding steel slags, their use in the manufacture of SCC has been reported [127,128]. The incorporation of steel slags has been reported to meet EFNARC workability requirements [112] and to exhibit an increase in mechanical properties [129].

Due to the previously mentioned considerations/observations, the incorporation of WFS as a replacement for fine aggregate can be a solution to the exploitation of raw materials, consequently reducing the environmental impact of NS exploitation and, simultaneously, creating a more sustainable material.

5.1. Physical properties

Martins et al. [44] studied the incorporation of up to 40% WFS as NS replacement in SCC. It was reported that the density increased from 0.80% to 2.31% with up to 30% WFS; however, the density observed decreased by 1.5% with a 40% WFS replacement. The decrease in density exhibited by the 40% inclusion of WFS may be attributed to its high absorption compared to NS, which generated a loss in the workability of the SCC, creating a less compact and more porous structure. A similar decrease was reported by Sua-iam et al. [130], who reported that the fresh density of SCC with WFS decreased from 1.20% to 1.60% within a 30 and 50% WFS replacement, respectively. Similar results were reported by Parashar et al. [131], who attributed the decrease in the density of the SCC to the lower density of the WFS compared to the NS. This reduction of density ranges from 1.69% to 6.12% with up to a 40% WFS replacement. In conclusion, changes in SCC density will depend on the difference between the density of NS and WFS, as well as the degree of substitution. Up to a 30% WFS replacement, there does not seem to be significant effects. Thus, careful consideration is needed to determine the optimal replacement rate for desired properties.

Regarding the water absorption of the SCC with WFS, Martins et al. [132] reported that SCC with a 20 and 30% WFS replacement fall under the category of low absorption and good quality concrete because their absorption percentage is less than 3%. SCC with a 10 and 40% WFS replacement presented medium absorption and quality, since the percentage of absorption was between 3% and 5%. According to another study by Martins et al. [44], replacing 20%, 30%, and 40% of WFS did not have a significant effect on the capillarity of concrete. SCC with a 30% WFS replacement showed better results, which could be attributed to a possible reduction in its pore connectivity and improved packing between its NS particles.

5.2. Fresh state properties

Sandhu and Siddique [37] reported that the workability of SCC decreases as the WFS replacement increases. This is so because the finer particles and impurities make the WFS more hydrophilic, attaching more water to its surface [37]. Martins et al. [44] studied SCC with the incorporation up to a 40% of WFS and reported that its workability decreased due to the rounded morphology and higher specific area of the WFS. Parashar et al. [131] studied SCC with up to a 40% of WFS replacement and a fixed proportion of fly ash at 25.5%wt. of total powder content. A loss of workability related to the increase of WFS replacement was reported, which was attributed to the WFS fines content and the angularity of its particles [131].

In contrast, Siddique and Sandhu [133] studied SCC with up to a 20% WFS replacement, reporting that 15% of WFS replacement improves the slump flow diameter by 3%. Additionally, it was reported that, with a 20% WFS replacement, the slump flow diameter decreased by 2.47%. An increase of the slump flow of SCC with a 50 and a 100% WFS replacement was reported to be attributed to the lack of fines in the WFS compared to the NS, which decreased the friction between the aggregates and the cement paste [134]. In summary, the loss in workability of SCC with WFS has been attributed to the fine and angular particles, as well as the impurities in the sand, with this effect being more noticeable with up to 40% replacement. Conversely, small WFS replacements have no adverse effect on the workability of SCC, and even large WFS replacements that have a small amount of fines can be beneficial to workability.

The findings of the literature reviewed regarding the slump flow are presented in Fig. 19. It can be seen that SCCs with WFS are classified into all three slump flow categories according to EN-206–1 [124]. In most cases, the incorporation of a 20% WFS results in a loss of workability, which can vary from 3% to 17%, possibly due to the variability of the WFS of each study. In cases where the slump flow increases with the incorporation of WFS, it may be explained seeing as the morphology of this by-product is rounder than NS, which decreases the flow stress and increases the viscosity [132,135].

Table 4 shows the summary of the findings reported by diverse authors [37,44,131]. The filling ability has been evaluated not only by the slump flow, as previously mentioned, but also by the t_{500} test and V-funnel test, while the passing ability has been assessed by the L-box test. It can be observed that the t_{500} times and V-funnel times increase with the inclusion of WFS in most cases, with these times being almost twice as long as those for SCC without WFS. According to Fig. 20, there is a linear correlation between the t_{500} test and the V-funnel test. It can be inferred that as the duration of the t_{500} test increases, so does the duration of the V-funnel test. As for the L-box test, the ratio required to be within EFNARC recommendations is achieved even with the incorporation of WFS, although in some cases, it tends to be lower than SCC without WFS. Generally, all the SCC manufactured with WFS match the EFNARC requirements [112].

5.3. Mechanical properties

Studies on the compressive strength of SCC with WFS show varied results. Generally, small percentages of WFS do not significantly affect the mechanical properties of SCC. However, these results vary

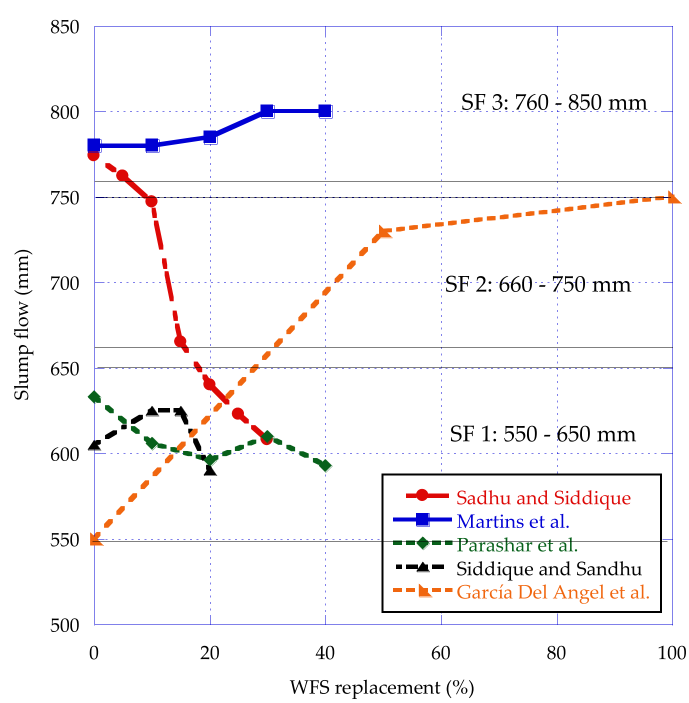

Fig. 19. Slump flow of SCC with WFS according to different authors.

Table 4
Workability of SCC with WFS according to different authors.

Reference	WFS (%)	Slump flow (mm)	t_{500} (s)	V-funnel (s)	L-box
[37]	0	774	2.14	4.56	0.96
	5	762	2.38	4.84	0.92
	10	747	2.73	5.12	0.93
	15	665	3.25	7.36	0.87
	20	640	3.46	8.45	0.89
	25	623	3.69	9.60	0.81
	30	608	3.98	10.72	0.85
[44]	0	780	3	5	0.96
	10	780	2	4	0.92
	20	785	3	7	0.96
	30	800	3	7	0.97
	40	800	6	12	0.97
[131]	0	633	5.88	12.33	0.78
	10	606	8.16	15.40	0.77
	20	596	8.33	16.72	0.83
	30	610	9.64	14.71	0.87
	40	593	10.80	17.52	0.85
[133]	0	605	-	7	1
	10	625	-	6.60	0.90
	15	625	-	6.28	1
	20	590	-	9.37	0.80

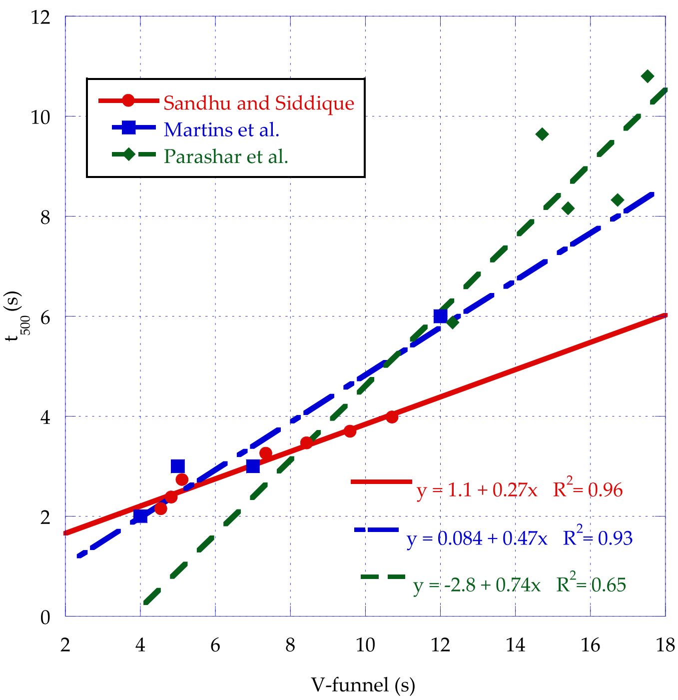

Fig. 20. Relationship between the t_{500} test and V-funnel test.

depending on the characteristics of the WFS used. Martins et al. [132] studied SCC with up to a 40% WFS replacement and reported a higher packing density between particles due to the continuous particle size distribution and spherical shape of the aggregates. This resulted in a lower water demand and a higher compressive strength at advanced ages for all mixtures. At 28 days, the SCC with 30% WFS showed a higher compressive strength than the control SCC, likely due to the denser composition resulting from the smaller particle size of the WFS [132]. Siddique and Sandhu [133] found that SCC's compressive strength increased by 14.80%, 22.73%, and 14.26% after 28 days with WFS replacements of 10%, 15%, and 20%, respectively, compared to the control SCC. An increase in SCC's compressive strength with partial and total WFS replacement has been reported to have occurred due to improved workability and better compaction capacity leading to a denser matrix than the one produced by the control concrete [134].

On the contrary, Sandhu and Siddique [37] reported a reduction in compressive strength at all ages (7, 28, 90, and 365 days) of SCC with up to a 30% WFS replacement. This was attributed to the poor properties of the silica content of the WFS, improper hydration, and insufficient binding of inert particles. In addition, Parashar et al. [131] reported a decrease in compressive strength from 5.8% to 37.4% with WFS replacements of 10%, 20%, 30%, and 40%. This was attributed to the higher fine content and binder traces of the WFS used, which weakens the ITZ [131].

In summary, the increase in compressive strength of SCC with WFS is due to a continuous particle size distribution, the spherical morphology of WFS, and a lower amount of fines compared to NS. The loss of compressive strength is attributed to a lower silica content and the presence of impurities in the WFS because of the binders used. The results reported by these authors are shown in Fig. 21. It can be observed that compressive strength losses are a function of the percentage of WFS replacement. The most significant strength losses start to occur after a 20% WFS replacement, where the strength decreases from 58 MPa to 49 MPa and from 34 MPa to 26 MPa. In cases where the compressive strength increases as a function of the WFS replacement percentage applied, strength gains begin to occur from a 10–15% replacement, with increases from 35 MPa to 40 MPa. Additionally, in cases where the replacement percentages are higher (up to 100% WFS), values of 35 MPa to 41 MPa are found.

5.4. *Durability*

5.4.1. *Rapid chloride penetration*

In their study, Martins et al. [136] investigated SCC with up to a 40% WFS replacement at 28 days. The results showed a 24.7% decrease in the RCP value for SCC with a 30% WFS replacement compared to the control SCC, suggesting a denser structure. It is important to note that all specimens had an electrical charge below 1000 Coulombs, indicating a very low risk of corrosion for all mixtures. Sandhu and Siddique [56] studied SCC with up to a 40% WFS replacement. It was reported that the RCP value did not improve with the use of WFS compared to NS. Additionally, the RCP value results of WFS mixes were similar to the control mix at all ages, as per ASTM C1202, and all the values for RCP improved with curing age (28, 90 and 365 days).

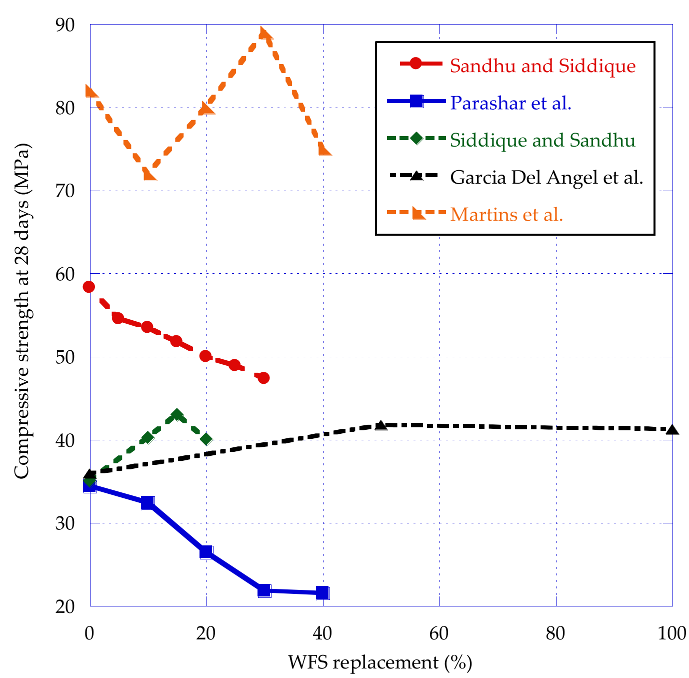

Fig. 21. Compressive strength of SCC with WFS according to different authors.

Siddique and Sandhu [133] reported that the increase of WFS replacement decreased the RCP value observed, being 15% WFS the optimal replacement. This percentage of replacement presented charges of 720 Coulombs compared to the other replacements that presented charges between 910 and 1200 Coulombs. This was attributed to the reduction of the voids of the SCC because of the fine WFS particles. When chloride ions penetrate the concrete and reach the reinforcement, they can initiate corrosion, leading to structural deterioration and reduced service life. By decreasing the permeability of SCC to chloride ions, the risk of chloride-induced corrosion is mitigated. The use of WFS in SCC densifies the concrete structure, thus reducing porosity and limiting the penetration of chloride ions.

Fig. 22 shows the findings reported in the literature perused. It can be observed that in most cases, the RCP value is in the range of 230–2000 Coulombs, which, according to ASTM C-1202–8 [137], classifies it as concrete with very low (100–1000 Coulombs) to low (1000–2000 Coulombs) chloride ion penetration.

5.4.2. Sulphate resistance

Sulphate resistance in SCC involves its ability to withstand the deteriorative effects of sulphate ions, ensuring the durability and long-term performance of the construction project/ construction projects. According to Martins et al. [132], who studied immersed SCC specimens into a magnesium sulphate ($MgSO_4$) solution at 5% for 180 days, replacing up to 30% of WFS in SCC, SCC with 30% WFS led to a 4.5% increase in compressive strength after 180 days, compared to the control SCC (90 MPa). This can be attributed to the better particle packing and improved internal porosity due to a lower void ratio resulting from the addition of WFS, which led to improved concrete density, hence reducing the penetration of aggressive agents [132]. Whereas the SCC with a 10 and 20% WFS presented compressive strengths around 85 MPa, representing a loss of 6% compared to the control SCC.

In the same study, a correlation between the void ratio and sulphate resistance was analyzed, finding a high correlation with a R^2 of 0.84 [132]. Siddique and Sandhu [133] conducted a compressive strength evaluation of SCC cubes with up to a 20% WFS replacement by immersing them in a 50 g/L $MgSO_4$ solution. It was reported that when comparing the compressive strength of SCC specimens immersed in water for 28 days with those immersed in the $MgSO_4$ solution for up to 56 days, the SCC with 10% WFS obtained the best results at all ages. The increases in compressive strength reported were around 14, 18 and 23% at 7, 28 and 56 days, respectively. The SCC with substitution percentages of 15 and 20% showed compressive strength losses of around 9, 6 and 3% at each of the ages [133].

Fig. 23 summarizes the findings in the literature consulted. In general, there is a tendency towards a loss of compressive strength when WFS is used. In the case of SCC subjected to 180 days of immersion in a $MgSO_4$ solution, the losses with 10% and 20% WFS are around 7% and 8%, respectively. Regarding SCC subjected to 7, 28 and 56 days of immersion in a $MgSO_4$ solution compared to SCC immersed in water for 28 days, it can be observed that SCC with 10% WFS presents a higher compressive strength at all ages, while SCC with 20 and 30% WFS present losses in compressive strength. Since there is a discrepancy between the results obtained, strong conclusions cannot be drawn. Therefore, further studies on this subject are suggested in order to obtain more enlightening results.

5.4.3. Ultrasonic Pulse Velocity

The UPV test is crucial for SCC due to its ability to ensure uniformity and quality, detect hidden flaws, estimate strength, and evaluate durability. It aids in real-time quality control during construction and contributes to advancing SCC research and application. The UPV test is specified in various international standards, including ASTM C597

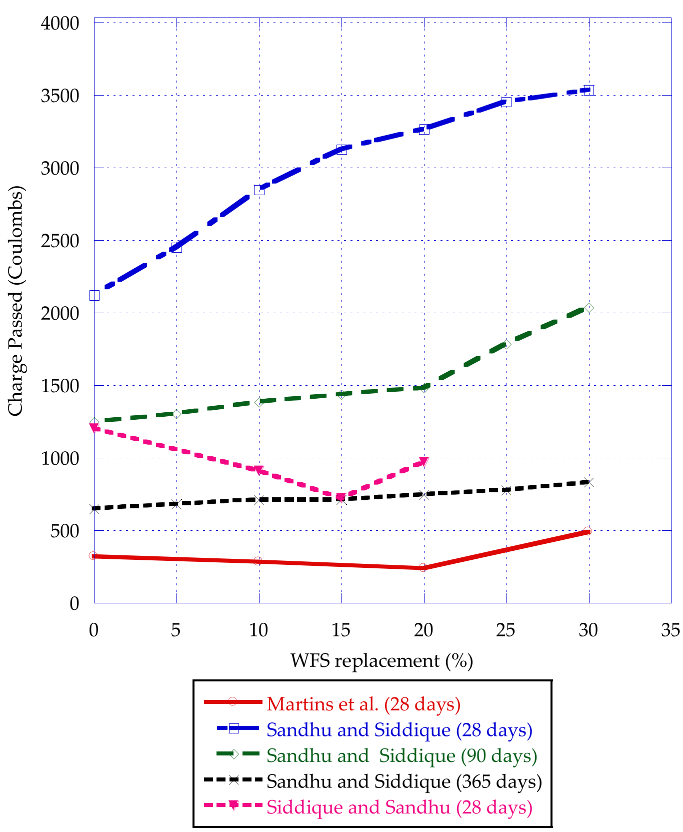

Fig. 22. Rapid chloride penetration of SCC with WFS according to different authors.

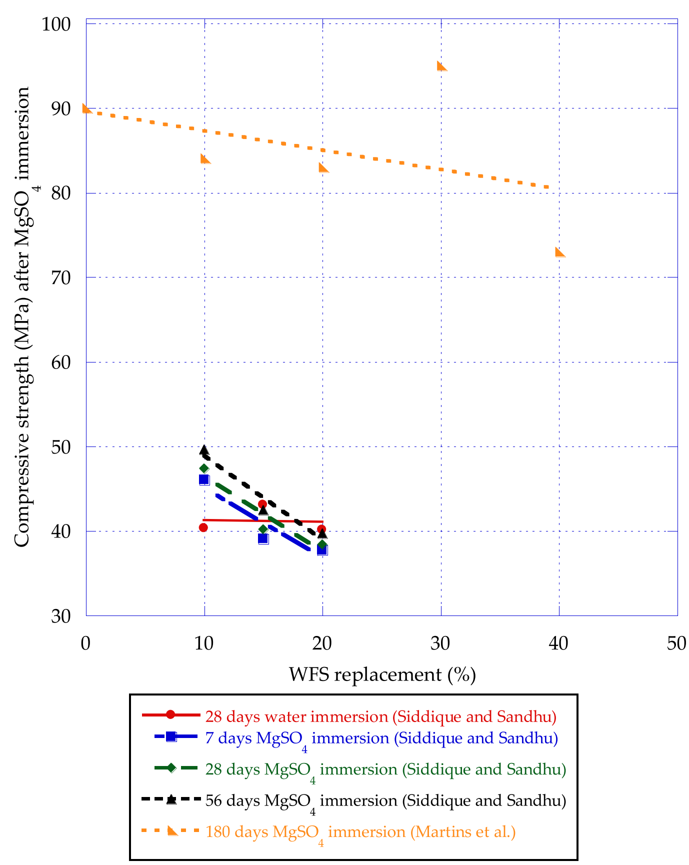

Fig. 23. Compressive strength of concrete mixes after immersion in $MgSO_4$ solution according to different authors.

[138] and EN 12504–4 [139]. Generally, the accepted range for UPV in good-quality concrete is 4.5–5.5 km/s, while values below 3.5 km/s indicate poor quality or potential structural issues.

Parashar et al. [131] studied the UPV of SCC with up to a 40% WFS replacement at 7, 28 and 90 days. It was reported that the UPV was higher than 4.5 km/s at all ages and all WFS replacements. This was because the WFS makes the concrete more porous. At 28 days the decrease of the UPV ranged from 1.24% to 7.28% with a WFS replacement ranging from 10% to 40%. At 90 days, a WFS replacement of 10% and 20% presented an UPV increase of 0.35 and 0.17%, respectively, being a minimal change. At the same age, the decrease of the UPV was approximately 3.35% with a WFS replacement from 30% to 40%. Also, Ashish et al. [140] replaced up to 50% WFS in SCC. UPV tests were carried out from 28 to 365 days of age. Results showed that replacements higher than 30% of WFS negatively affected the UPV at early ages. Despite all the SCC specimens being in the range of good quality concrete.

In Fig. 24, the UPV results of SCC with WFS exhibit values between 5.2 and 5.6 km/s at 28 and 90 days, indicating that the UPV value increases with age notwithstanding its WFS replacement ratio. It can be concluded that SCC with up to 50% WFS can be categorized as a good quality concrete based on its UPV value. This means that it is a concrete with a dense and uniform structure with a suitable potential for use in structures, as long as a strict quality control is maintained.

5.4.4. Acid attack resistance

The importance of addressing acid attack in SCC lies in its potential to compromise the durability and structural integrity of SCC constructions. Maruthachalam et al. [141] found that acidic reactions in cement paste form soluble calcium salts, therefore reducing the strength and porosity of structural concrete. Hydrochloric acid (HCl) is particularly aggressive to concrete, according to Allahverdi and Skvara [142], as it easily produces calcium salts and causes significant mass loss.

Regarding SCC with WFS, Martins et al.[44] subjected SCC mixes with up to a 40% WFS replacement to immersion in HCl for 75 days. The results indicated that the inclusion of 40% WFS increased the compressive strength of the SCC by 41% compared to the control SCC (50.1 MPa). Meanwhile, the increases in SCC with 10%, 20%, and 30% replacements were 18%, 30%, and 37%, respectively. This enhancement

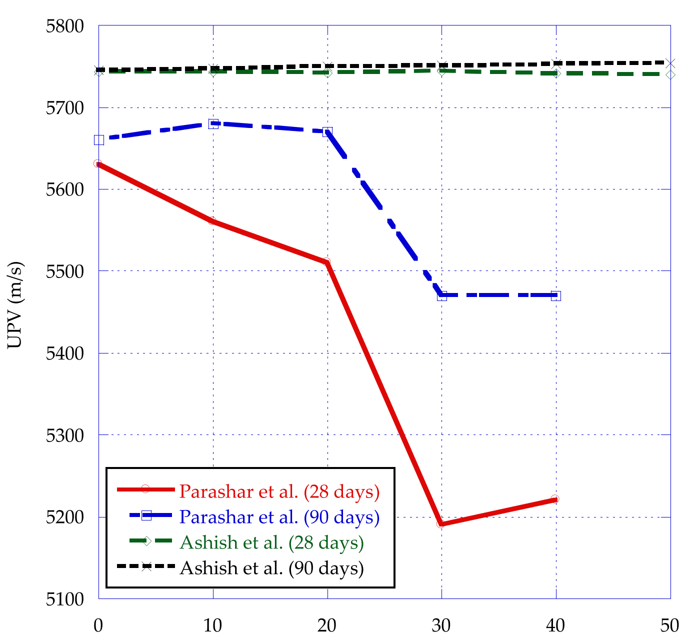

Fig. 24. Influence of WFS on SCC in UPV tests according to different authors.

in compressive strength was attributed to its higher fine silica content. Furthermore, the study concluded that lower porosity correlated to a reduced susceptibility to acid attack on concrete [44]. The resistance to acid attack of SCC with WFS may be due not only to the high silica content but also to the fineness, which is usually higher than that of NS, producing a denser and more compact material, which decreases its porosity. Low porosity makes the concrete less prone to acid attack, consequently increasing its durability.

6. Techno economic analysis

From an economic standpoint, few studies have reported on how the incorporation of WFS influences the production cost of concrete. In India, the price of NS is reported to be 800 rupees (9.64 USD) while the price of WFS is 40 rupees (0.48 USD) [145]. In this regard, Thiruvenkitam et al. [20] reported that using 20% WFS in the production of 1 m^3 of M30 grade concrete saves around 7.5%. For M25 grade concretes it has been reported that the inclusion of WFS up to 60% reduces the cost of 1 m^3 by 3.50% [146]. In Brazil, dos Santos et al. [147] reported that the price of 1 m^3 of concrete is 53.68 USD. By completely replacing NS with WFS, the cost of concrete was reduced to 48.62 USD, a reduction of 9.5%. This is because WFS is freely available as waste material [147]. In Mexico, the estimated price of 1 m^3 of concrete with a strength of 150 kg/m^2 is 130.88 USD, with the estimated price of NS being 13.16 USD per m^3. Since there is no information on the price of WFS and assuming it has no cost, the price per 1 m^3 can be reduced by 10%, which is similar to what dos Santos et al. [147] established.

These findings underscore the economic benefits of utilizing WFS, which is readily available as waste material. While specific cost savings may vary depending on factors such as the degree of substitution and material prices, the potential for substantial savings is evident across different regions and concrete grades. Further research in this area can provide valuable insights into optimizing concrete production processes and reducing their associated costs.

7. Challenges and Paths Forward in using WFS

In this work, the characteristics of mortars, concrete, and SCC with the incorporation of WFS have been reviewed. In most cases, a loss of workability and mechanical strength is reported with replacement contents greater than 20%. Hence, one of the main challenges is the utilization of higher replacement volumes while maintaining workability and demonstrating adequate mechanical strength. To achieve this, a viable alternative may be the pre-treatment of WFS; several authors have shown that treating WFS through water washing [58], acid treatment [59] and fungal treatment [92] reduces impurities around its particles.

Another challenge is the variability of its physical and chemical properties. Researchers, engineers, or architects wishing to work with WFS must take into account that changes in these properties vary depending on the type of binder used and the number of times it has been reused. The aforementioned aspects will influence the density, absorption, and fineness of the WFS, which can affect workability, consequently mechanical strength, and ultimately the durability of concrete. Regarding its chemical composition, it is known that WFS contains high contents of SiO_2; when analyzing WFS, it must be ensured that its content is high because low contents are linked to losses of mechanical strength [37].

Regarding the environmental issues associated with the use of WFS, it has been reported that it is not toxic, corrosive, or combustible [143]. Concerning leaching problems, concrete made with WFS has been reported not to pose an environmental hazard [52]. Cioli et al. [144] reported that in general, WFS is not hazardous in accordance with the European legislation, also, it was reported that regarding the variability of WFS, in general, the metal leaching is almost always below the limits imposed by current regulations [144].

In summary, incorporating WFS in mortars, concrete, and SCC offers environmental benefits, but challenges persist in maintaining workability and mechanical strength, particularly at higher replacement levels. Pre-treatment methods like water washing and acid treatment can mitigate these challenges. Variability in WFS properties requires careful consideration in mix design. However, WFS is deemed environmentally safe and compliant with regulations. Further research is needed to optimize its use in concrete production for sustainable construction practices.

8. Conclusions

In this systematic review, various aspects of WFS and its potential applications in mortars, concrete, and SCC, were explored. The following conclusions are the result of this work:

- WFS contains traces of binders, mainly bentonite clays. These binder residues, the fineness and the subangular to round morphology of WFS are the main causes of the loss of workability.
- The density of WFS is usually between 2.24 and 2.80 g/cm^3. While the absorption and fineness modulus range from 0.33% to 7.77% and 0.50–3.20 respectively. The WFS is mainly composed of SiO_2, up to 98.59%.
- In concrete, WFS exhibited minimal impact on density, between 1.45% and 3%. Workability tends to decrease with increasing WFS, although a replacement of up to 10% does not present high variations. A higher replacement can result in losses from 20% to 80% of workability. The compressive strength gains vary from 5% to 12% with up to a 50% WFS replacement.
- The incorporation of up to 20% of WFS in SCC decreases workability within a range of 3–17% due to finer particle size and impurities. The compressive strength can increase by up to 14% with 15% of WFS. However, the loss of compressive strength becomes more evident starting from a 20% replacement.
- The variability in the results found in workability, mechanical strength, and durability may be due to differences in composition, fineness modulus, type of binders, and replacement rate used.
- The incorporation of WFS results in material cost savings ranging from 7.5% to 10%. This will depend on the degree of substitution and the prices of materials in each country.

In summary, while incorporating WFS in mortars, concrete, and SCC offers environmental benefits, challenges remain in workability and strength, particularly at higher replacement levels. Pre-treatment methods like water washing and acid treatment can help, but a careful mix design is necessary due to variability in WFS properties.

CRediT authorship contribution statement

Gilberto Garcia: Writing – original draft, Formal analysis, Data curation, Methodology. **René Cabrera:** Visualization, Validation, Formal analysis, Conceptualization, Methodology, Writing – review & editing. **Julio Rolon:** Writing – review & editing, Visualization, Resources. **Roberto Pichardo:** Resources, Visualization, Writing – review & editing. **Carlos Thomas:** Writing – review & editing, Validation, Formal analysis.

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.

Data Availability

No data was used for the research described in the article.

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