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Review

A state-of-the-art review of Waste Foundry Sand concrete from an optimisation perspective

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ABSTRACT

Waste Foundry Sand (WFS), a by-product of the cast metal industry is produced in quantities exceeding 100 million tons annually. Being a high-quality silica sand, it poses a potential solution for reuse within concrete as a fine aggregate replacement; simultaneously addressing the increasingly critical issue of foundry waste generation and mitigating the overextraction of natural aggregates for concrete production in line with United Nations Sustainable Development Goals. It is widely understood that partial WFS substitution as a fine aggregate within concrete is not only acceptable but often beneficial, however the variability in the properties of WFS concrete has yet to be systematically tracked and categorised. This state-of the-art-review provides a succinct and detailed assessment of the typical impact of WFS on concrete performance, highlighting variability in properties, and recent advancements for optimisation. Analysis of the lesser examined facets, such as WFS treatment and combination with supplementary cementitious materials is undertaken to provide a robust methodology for WFS concrete optimisation via effective research collation and impact categorisation. Existing studies on long-term durability, and life cycle assessment in terms of both environment and economics, are highlighted as lacking comprehensive insight and thus create a framework for future research.

1. Introduction

Waste Foundry Sand (WFS) is a by-product of the cast metal industry arising from the sand mould used to manufacture cast metal parts. The high-quality sand used within casting moulds facilitates reuse multiple times prior to eventual degradation, at which point it is crushed and deemed WFS, sometimes also referred to as spent foundry sand or simply foundry sand. Approximately 100 million tons of WFS is produced annually [1] with around one ton produced for every ton of cast iron or steel product [2]; in the UK specifically, more than one million tonnes are disposed of annually [3]. The cast metal process relies on virgin foundry sand as the primary material for producing mould boxes. Binding agents are blended with the sand to facilitate compaction around a pattern that replicates the component to be cast. Once the mould is prepared, molten metal is poured into the sand box and left to solidify. After cooling, the mould is broken apart, and the casting removed. The used sand is then crushed and screened, with a portion reclaimed for further casting cycles and the remainder deemed WFS; this life cycle is illustrated in Fig. 1.

Historically, much of this waste product has been landfilled; it is estimated that only 15 % of WFS is recycled due to processing costs [4]. Recently however, research into the feasibility of reuse has been conducted, publications on WFS management have increased

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38-fold from 1971 to 2020, with keywords such as 'Waste Foundry Sand' experiencing growth in the region of 2700 % [5]. There is strong evidence linking the majority of this research to the construction materials sector [6], evidencing that WFS could be successfully used for soil stabilisation, brick and block manufacturing, ceramics, road construction, and fill material [7]. Perhaps the most promising avenue of WFS reuse however is as fine aggregate replacement within concrete production. WFS concrete presents an active field of global research where it is widely established that partial replacement can produce a good quality, sustainable alternative to conventional concrete.

Alongside significant foundry waste management issues is the increasing consumption of virgin fine aggregate as a result of continuous growth in the concrete sector. Approximately 40–50 billion tonnes of aggregate is extracted from the natural environment annually [8], of which, it is estimated over half is consumed by the concrete industry [9]. Further estimations anticipate building sand usage to increase by 45 % by 2060 [10]; the true extent of this problem has been explicitly outlined by the United Nations who deemed it unfeasible to assume the sand requirement for future populations can be met without intervention [8].

Assessment of current WFS concrete review articles provides the ability to draw generic conclusions as to the common properties. Research shows evidence of reduced workability, increased water absorption, and improved durability and strength properties when compared to a control sample. This usually applies up to an optimum fine aggregate replacement in the region of 15–30 % by weight for standard concrete [1,2,4,6,7,11,12–17]. Noteworthy however, is the significant variation in WFS dependent on the type of casting process, metal type, employed technology, furnace, finish, [18] and even source within the foundry [19], resulting in a subsequent impact on the ensuing WFS concrete.

The current state-of-the-art review addresses a significant gap in the literature, in terms of providing a means of categorising the subsequent impact on WFS concrete by a critical review process and data collation. For the first time, collation of research into the advancing landscape of WFS concrete is conducted in terms of assessment of economic and environmental life cycle, as well successful treatment methodologies and targeted combination blends to improve both engineering performance and reduce contamination potential. The review provides novelty by evidencing clear gaps in the knowledge of WFS concrete performance which limit its use on a large scale, particularly with respect to its durability characteristics, but also its use alongside Supplementary Cementitious Materials (SCMs). WFS reuse poses a potential solution to not only management of manufacturing waste disposal, but also the over extraction of virgin sand resource from the natural environment. Should a structured and succinct summary of the current understanding be available to engineers, more rapid and sustainable progression to industry is likely.

It is noted that the physical and chemical properties of raw WFS have been extensively researched, with significant data collation and comparison provided in many of the previously referenced review articles. The intention of this review is to not repeat this work but instead focus on WFS concrete properties with a summary of the aforementioned outlined for understanding. There are two main types of foundry sand, both quartz-based, and distinguishable by their bonding systems. The first are known as greensands and use clay as a binder, typically consisting of 85–95 % silica, 0–12 % clay, 2–10 % carbonaceous additives and 2–5 % water, as well as trace metals [20]. The second are chemically bonded sands, employing polymer activated by a catalyst, consisting of 93–99 % silica and 1–3 % chemical binder. The most common chemical binder systems include phenolic-urethanes, epoxy-resins, furfuryl alcohol, and sodium silicates [21]. It is believed that the variability in properties and performance of clay bound versus chemically bound WFS is

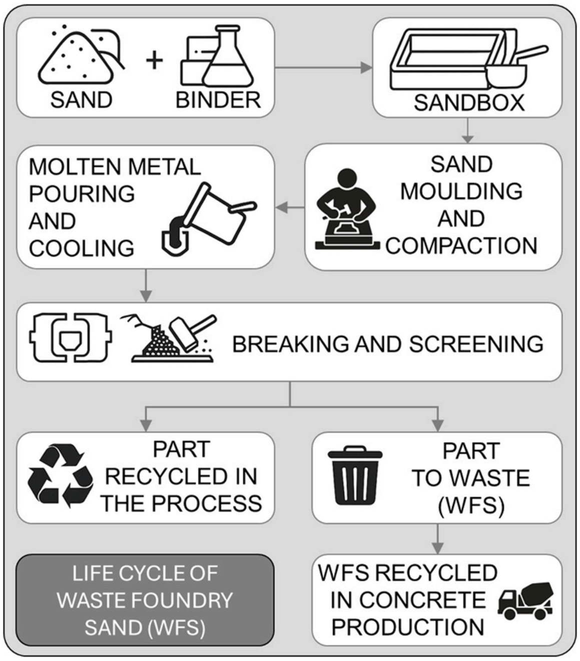

Fig. 1. Flow chart of WFS product life cycle.

significant [22]. Loss on ignition (LOI) typically ranges from 1.5 to 7 %, with greensand displaying increased LOI compared to chemically bonded sand [23].

WFS has been classified as non-hazardous waste by the European Union [24]. Most organic material is burned off during the casting process, yet, has potential to transform into hazardous compounds under incomplete combustion [20]. In comparison to virgin sand, the metallic content in WFS is marginally higher [25] and largely dependent on casting type and methodology [26]. Leaching concentrations are also typically below contamination limits [27] and not dissimilar to those shown in natural soils and other construction materials [20]. WFS pH is similar to that of a natural sand, varying from 4 to 8 depending on binder and metal type [28]. Critically, there is evidence of notable inconsistency in the chemical properties of WFS; organic, metallic, and contaminant content vary and care must be taken in terms of characterisation.

In terms of physical properties, WFS tends to retain a similar, or marginally lower density than that of a natural sand (2.28 – 2.60) [29–32], with typical sub-angular to rounded particle shape [22,23,33,34–36]. WFS is reported as being of finer nature than standard sand [31,32,35,37–41], with reduced fineness modulus likely contributing to the often-increased absorption and water demand. Chemically bound sand is typically denser, has higher specific gravity, and lower absorption than greensand [20,23,40]. There is again significant variability in WFS physical properties, with such variance highlighting the need for individual characterisation. The impacts that such physical and chemical properties have on concrete made with WFS are discussed in the following sections.

2. WFS concrete critical review

2.1. Fresh properties of WFS concrete

The inclusion of WFS in concrete leading to workability reduction has been widely reported within literature [18,35,41–49]. WFS concrete often requires superplasticizer to retain workability whilst minimising excess void content and its associated negative impact on strength and durability properties. Consequently, the reduced workability within WFS concrete is one of the main factors limiting increased replacement. WFS fineness provides increased potential for drawing water from the mix, in turn reducing workability. It is also suggested that WFS fineness increases the surface of hydration products, causing higher absorption [43]. It has been reported that chemically bound WFS concrete is able to retain higher workability as compared to greensand [50], owing to the presence of clay and impurities in the latter causing increased water demand and reduced fluidity [51].

The impact of WFS content on slump of OPC concrete is displayed in Fig. 2, key details that may affect workability are included in Table 1.

It is clear that increasing WFS causes a reduction in slump, typically tolerable until around 30 % substitution prior to more rapid loss. Conversely, other research has reported improvements with WFS inclusion [22,54]; at times with extremely workable concrete at slumps of 200 mm [51]. The latter may be due to high superplasticizer content and water/binder ratios; yet the importance of aggregate grading on workability in this case may be highlighted by cross-study comparison. Siddique et al. [42] used nearly twice as much coarse aggregate as fine, where Basar and Deveci Aksoy [51] used near equivalent amounts, with the well graded proportions likely contributing to more than twice the slump at the same replacement. Comparing the studies of Siddique et al. [41] and Singh and Siddique [47], it may be concluded that the water binder ratio can be effectively reduced whilst retaining the same workability through increased superplasticizer content. Ganesh Prabhu et al. [43] suggest adjusting water content to achieve desired workability,

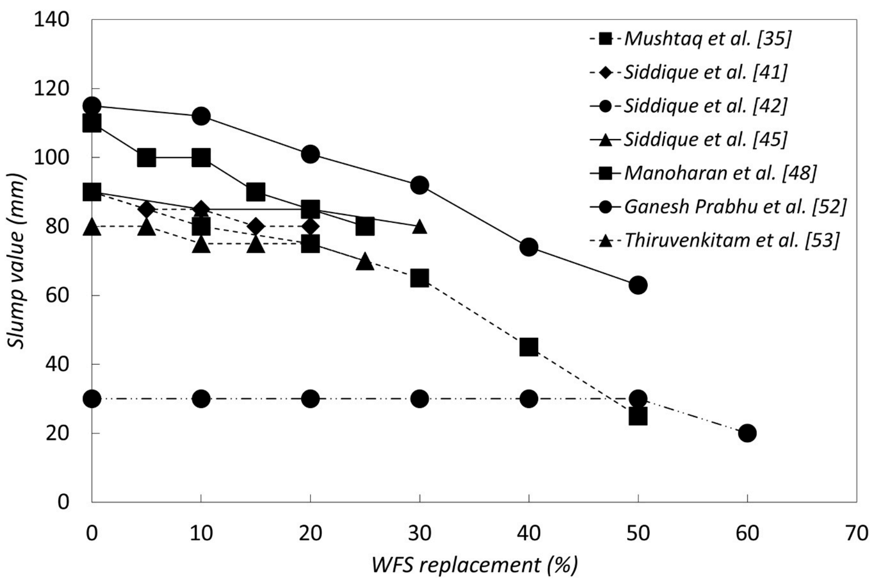

Fig. 2. Impact of degree of WFS replacement on slump.

Table 1
Key details with potential to impact workability.

Variable	[35]	[41]	[42]	[45]	[48]	[52]	[53]
W/C ratio	0.4	0.5	0.50–0.56	0.5	0.5	0.44	0.45
Superplasticizer content	0.9 kg/m^3	0.59 L/m^3	1.75 kg/m^3	4.5–5.9 L/m^3	-	-	-
Testing standard	BIS:1199–1959	BIS:1199–1959	BIS:1199–1959	BIS:1199–1959	BIS:1199–1959	-	-

though it is understood that adverse impacts may occur if not conducted effectively.

Workability has been tested in mixes with 100 % WFS substitution [46,55] displaying significant workability reduction, in one case down to 0 mm. Slump loss over time has been measured where workability loss was approximately the same as control samples throughout [43]. Basar and Deveci Aksoy [51] suggest there may be setting time delay due to the presence of finer particles, however, differences in comparison to control samples are minimal. Many have outlined that beyond 30–50 % replacement, reduced fluidity and workability begin to have a detrimental impact on concrete performance [1,13,18]. This is common across all assessed publications, raising the challenge of ensuring adequate workability can be maintained when maximising WFS replacement.

2.2. *Physical and mechanical properties of WFS concrete*

Hardened density is directly linked to both the mechanical and durability properties of concrete. Given WFS density is typically lower than that of standard sand, WFS concrete density is also typically lower than that of conventional concrete. Previously outlined poor compaction leading to increased void content, also has potential to impact density, hence, as previously discussed, many researchers exercise the use of superplasticizer to retain adequate workability and compaction. It is widely understood however, that the incorporation of superplasticiser in its own right significantly impacts mix properties, providing potential for 25 – 35 % reduction in water content [56] or significant workability enhancement via improved particle dispersion [57]. Such mix variation has clear potential for subsequent impact on mix density and porosity, where typically a more refined pore structure with increased density is evidenced [58,59]. Variation has been reported however, Puertas et al. [58] displayed both increased and decreased total porosity in cement pastes with varying superplasticiser dosage in the range of 0 – 1 % by mass of cement, where the relative magnitude of change has been outlined in a range of −0.51 % to + 1.37 %. It is also understood that excess superplasticiser may cause bleeding and segregation, mechanisms that induce additional mix porosity through inconsistent particle dispersion and curing. The variation in porosity, and subsequently linked density properties of WFS concrete incorporating superplasticizer must therefore be carefully assessed in understanding the magnitude of variation attributable to both types of addition, particularly given the authors are aware of no studies explicitly outlining the combined impact of such. The same is true for mechanical properties, and hence assessment from a more global perspective through generic trends is more suitable in this case, and accounts for variation due to aforementioned mechanisms.

Research has outlined density results in the range of 2190 – 2334 kg/m^3 with worst case reductions of 3.95 % [51] and 3.29 % [54]. Both studies used consistent superplasticizer addition of 1.81 % [51] and 0.57 % [54] respectively, displaying reductions in density with increasing WFS. Such results suggest density variation in this case is mostly a function of either the sand density itself, or WFS induced pore structure variation, and less so related to the superplasticizer effects discussed previously; nevertheless, all densities

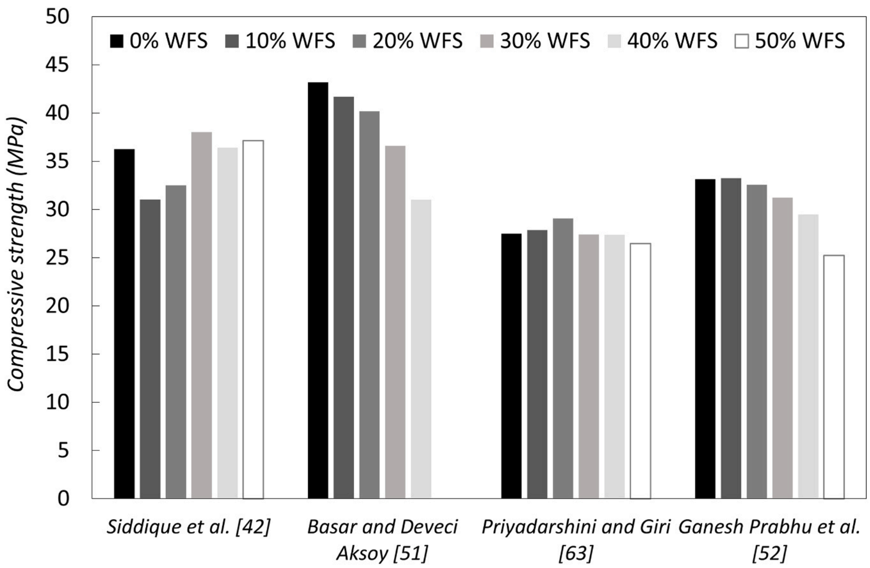

Fig. 3. Typical trends in variation of 28-day compressive strength with degree of WFS replacement.

remain within the range of a standard concrete. Smarzewski and Barnat-Hunek [60] evidenced similar results with consistent plasticizer content, where WFS sample densities reduced in comparison to control. Martins et al. [61] displayed results indicating consistent specific gravity with no superplasticizer addition, varying little from control samples, with the maximum value showing an increase in the region of 1 % at 40 % WFS replacement. Such results are somewhat contradictory to aforementioned studies and are likely related to micro filling of voids with finer WFS particles. Nonetheless, it is clear there appears to be no significant negative impact on density with WFS inclusion.

Due to the largely variable nature of concrete design properties, including but not limited to mix proportions, additives, sample preparation, material variation, curing periods and design strength, it is difficult to draw direct numerical comparisons between a large number of discrete studies. Hence, more generalised conclusions in terms of major trends are made herein by analysing strength properties as a whole. Typical trends in compressive stress variation with WFS replacement are shown in Fig. 3. The four studies identified are representative of the main compressive strength behaviours reported within 20 separate studies across literature.

The first trend identified [42] is that of an initial decrease in compressive strength when compared to a control sample, followed by an increase up to an optimal point, then finally, a marginal decrease as WFS percentage rises. Such behaviour has also been shown by Mushtaq et al. [35] and Rahman et al. [29]. Another common trend is that displayed by Basar and Deveci Aksoy [51], wherein a decrease in compressive strength is shown in comparison to control samples at all replacement percentages. The magnitude of this reduction increases as WFS increases and is often deemed tolerable up until a certain percentage replacement, typically around 30 %. Similar results have been reported by Ahmad et al. [18] and Khatib et al. [62]. Potentially the most common of the three broadly identified trends is that displayed by Priyadarshini and Giri [63] which has also been observed in other studies [44,47–49,53,64,65]. Here, an increase in compressive strength is shown in comparison to control samples up to an optimal replacement percentage, at which point a continuous decrease is shown as replacement increases. Authors have also reported continuous increase in compressive strength without the corresponding drop [30,45].

The study of Ganesh Prabhu et al. [52] shows results reflective of a combination of the two previous trends. Here, an initial increase in compressive strength is shown, but of a small magnitude making it highly comparable to that of the control sample yet still reaching an optimum prior to continuously decreasing. Similar behaviour has also been reported [43]. More variable results have been shown by Mavroulidou and Lawrence [22] where compressive strength increase with green WFS was not statistically significant. The variation in compressive strength of WFS samples when compared to control samples appears to reduce with curing period. This trend is illustrated in Fig. 4, where despite mix design, degree of replacement, and magnitude of compressive strength it is clear there is a convergence towards the performance of the control samples with time. The more significant standard deviation in this case further reflects this fact, highlighting the variation with degree of WFS replacement as being somewhat significant, yet still evidencing a clear trend of convergence.

Contrary conclusions have been shown however, with results not converging as distinctly [19]. The impact of water/binder ratio on compressive strength of WFS concrete was tested by Mavroulidou and Lawrence [22], with 0.55 and 0.45 ratio mixes. At 28-day curing, the average increase as compared to control samples was 1.13 % for W/C= 0.55, and 5.43 % for W/C= 0.45; suggesting that higher W/C produces compressive strength values akin to those of control samples. Monosi et al. [19] suggest advantages in terms of compressive strength are negligible when W/C is reduced below 0.5; the strength reduction shown due to incorporation of WFS was exacerbated by reducing W/C. Other research, however, has identified WFS mixes with higher strength than control samples with W/C below 0.5 [22,35,44,47,52,53,64,65].

Fig. 4. Average difference in compressive strength of WFS samples as compared to control samples as a function of age in days (d) Error bars show standard deviation.

It is clear that the compressive, tensile, and flexural strength properties tend to follow similar trends in terms of variation based on both curing period and WFS replacement percentage, having been clearly demonstrated by numerous researchers [18,35,42–45,47,48,49,51,53,64,65]. Naik et al. [66] and Siddique et al. [42] were able to show similar consistency with ratios of tensile to compressive strengths remaining between 10 – 11 % and 5 – 7 % respectively. A further illustration of the comparative nature of the strength properties is displayed in Fig. 5.

It is evident that despite the magnitude of strength increase varying across the different properties, the maximum variation is at the same WFS replacement percentage, highlighting a strong connection between such properties. Such findings are further reinforced by Mavroulidou and Lawrence [22], whose results did not show consistent or predictable strength values with WFS replacement percentage, yet still retained a consistent optimum across all strength properties at a given W/C. Research has suggested that the fine nature of WFS contributes to a denser matrix, subsequently contributing to strength properties [18,30,41,42,45,47,64,65]. The impact of silica content and particle regularity have also been attributed to an increase in compressive strength [22,45,65]. Many authors have attributed reductions in compressive strength to increased WFS fineness causing a reduction in water-cement gel in the matrix and hence leading to poor binding of aggregates [18,47,51,64,65]. This may be further explained by an increased water demand due to the fine nature WFS, which reduces the amount of free water in the mix and hence limits the production of cement paste resulting in a weaker ITZ. An indication of such inferior bonding has been demonstrated by de Paiva et al. [67], where both voids and reduced interlocking of WFS particles to cement paste are evidenced. SEM images show C-S-H definition and adhesion to aggregate worsening with increasing resin content of WFS, which the authors attributed to reducing mechanical capacity. Siddique et al. [42] have however, evidenced both positive and negative impact on C-S-H spread and matrix bonding with WFS inclusion depending on replacement percentage. These contrasts highlight the necessity for further research into the ITZ and bonding characteristics of WFS within cementitious matrices in facilitating understanding of the contribution of such to compressive strength reduction, and subsequent performance optimisation. Others have attributed reductions to WFS fines increasing water demand, reducing workability, and consequently resulting in poor compaction and increased voids [18]. This has been reinforced by Ganesh Prabhu et al. [43] who were able to illustrate a strong linear relationship between both workability and density with compressive strength. The contribution of WFS binder and impurities to reduced compressive strength has also been highlighted [19,43,51,66]. Many explanations for the variation in compressive strength of WFS concrete are based on generic assessment of trends with increasing replacement, WFS composition or shared research understanding that lacks substantiated evidence. Further detailed investigation into the role of WFS impurities, binder, fineness and water demand on bonding and hydration mechanisms are required to confirm commonly referenced hypotheses.

Mavroulidou and Lawrence [22] have illustrated a strong correlation between Modulus of Elasticity (MOE) and compressive strength within WFS concrete. A number of authors have been able to show an increased MOE as compared to control samples [30,45,47,48,53,64,65], with contrary results shown elsewhere [43,51]. There remains no clear consensus on the effect of WFS on MOE.

In summarising suitable WFS substitution based only on mechanical properties; studies have demonstrated good performance at 20 % replacement [41,43,47,48,51,63–65], 30 % replacement [18,19,35,44,45,48,49,52,53], 50 % replacement [42,61] and even full replacement [22]. Typical trends have been identified, yet variation across studies is significant further highlighting the necessity of WFS analysis on a case-by-case basis.

The few studies that have assessed WFS concrete shrinkage have been compared in Table 2.

It appears that an increase in WFS causes an increase in drying shrinkage, usually within tolerances provided by standards. Such behaviour is mostly explained by impurity content, where other authors have provided similar reasoning in terms of increased absorption capacity being a key contributor [12]. It is clear that there is a distinct lack of research with respect to such time dependent properties, where further work would prove beneficial.

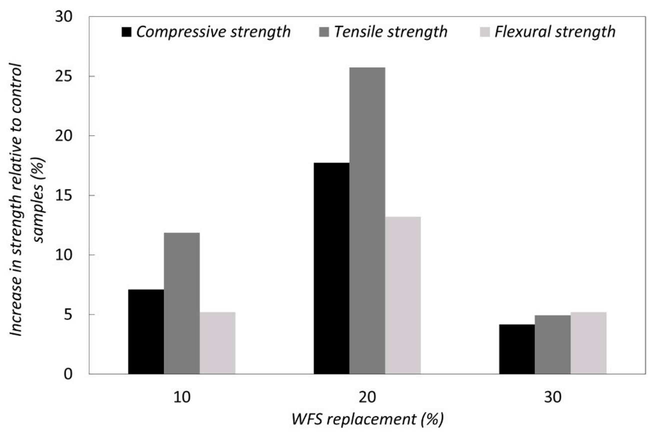

Fig. 5. Increase in 28-day strength properties at different degrees of WFS replacement as compared to control samples, data from Saha et al. [49].

Table 2
WFS concrete drying shrinkage research comparison.

Source	*Testing method*	*WFS replacement (%)*	*Main findings*	*Authors explanation of findings*
[35]	Drying shrinkage (ASTM C157–2003)	0–50	Increased drying shrinkage with increasing WFS, initially increased shrinkage rate with WFS, all samples within ACI209.1R-05 limits	Increased WFS compressibility, clay and impurities absorbing water and shrinking whilst drying
[55]	-	0–100	Systematic increase in drying shrinkage with increasing WFS	-
[68]	Drying shrinkage (ASTM C426)	0–35*	Increased drying shrinkage with increasing WFS, all samples within standard limits	-
[69]	Volumetric variation (ASTM C490–2017)	0–100	Decreased early shrinkage in WFS samples, followed by significant increases as compared to control with curing period	Water adsorption onto bentonite/coal particles resulting in reduced effective water-cement ratio and flowability

Notes: *25–35 % fly ash as SCM

Table 3
WFS concrete water absorption research comparison.

Source	**Testing method**	**WFS replacement (%)**	**WFS impact**	**Other findings**	**Authors explanation of findings**
[18]	Immersion absorption (ASTM C642–13)	0–50	Increased absorption with increased WFS	Minimal impact up to 30 %	Increased WFS surface area causing reduction in cement gel and inferior binding
[22]	Immersion absorption (BS EN1881–122:2011)	0–100	Variable, but general decrease in absorption with increased WFS	Better performance above 30 %, optimal at 100 %	Reduced voids due to WFS filler effect
[30]	Immersion absorption (-)	0–100	Reduced absorption with increased WFS	Optimal at 100 %	Increased packing due to WFS fineness, denser matrix
[36]	Immersion absorption (ASTM C642)	0–15	Initial increase, then general decrease in absorption with increased WFS	Optimal at 15 %	Reduced voids due to filling effect of clay
[46]	Immersion absorption ABNT NBR9778 2005 / ASTM C642–13)	0–100	Increased absorption within WFS samples	-	-
[46]	Capillarity absorption (ABNT NBR9779 2012 / ASTM C1585–13)	0–100	Increased absorption within WFS samples	Samples including WFS from landfill tended towards control sample over time	Increased porosity of WFS samples
[48]	-	0–25	Increased absorption with increased WFS	Reduced absorption up to 10 % WFS replacement	WFS particles improve packing up to 10 % beyond which additional fine material not required
[51]	Immersion absorption (TS EN480–11:2008)	0–40	Linear increase in absorption with increased WFS	20 % replacement tolerable as per TS2824 EN1338:2005–04	-
[53]	-	0–25	Increased absorption with increased WFS	Absorption constant beyond 20 % due to reaching absorption equilibrium	WFS increases absorption capacity by increased surface area, modifying pore structure
[54]	Immersion absorption (ASTM C642–13)	0–100	No impact on absorption up to 50 % WFS, sharp increase beyond (56.6 % increase at 100 % replacement)	-	-
[61]	Immersion absorption (ABNT NBR9778 2005)	0–50	Reduced absorption with increased WFS	Optimal at 40 %	-
[62]	Capillarity absorption (similar to ASTM C1585)	0–100	Increased absorption with increased WFS	Direct correlation between absorption and compressive strength	Unimodal grain distribution of WFS, inferior packing, larger pore volumes
[67]	Immersion absorption* (ASTM C642–13)	0–50	Increase in absorption with increased WFS	Tolerable up to 50 %	Increased WFS surface area, hence higher water demand, reduced workability and reduced hydration
[73]	Immersion absorption (ABNT NBR9778)	0–100	Increased absorption within WFS samples (69 % increase at 100 % replacement)	-	Increased water demand of clay particles

Notes: *Testing conducted on mortar

2.3. Physical and chemical durability properties of WFS concrete

The durability properties of WFS concrete are an increasingly popular branch of active research, however it is an area that many suggest significant investigation is still required. The durability properties of a structural element are of prime importance with respect to environmental, financial, and safety concerns. A more durable concrete member can instil a higher level of confidence in a prolonged service life, in turn reducing the requirement for additional maintenance and ultimately extending the period prior to eventual replacement. The resilient design of infrastructure as a means of combatting climate change has been outlined by Goal 9 of the United Nations Sustainable Development Goals [70], of which the eradication of poor structural durability can contribute to such an achievement. Market research within the UK has outlined the significance of poor durability, highlighting the current approach for structural longevity enhancement as being the use of additional cementitious materials [71]. It has been suggested that a 50 % elongation in service life of 'in-use' cement-based structures could reduce the demand for cement by as much as 14 % [72], emphasising the importance of durability verification for concrete applications. Despite this, as compared to mechanical property investigation, research into WFS concrete durability has been largely overlooked. Collation of available literature can provide an indication as to the impact of WFS on durability properties and help identify knowledge gaps limiting implementation on an industrial scale. The porous nature of concrete and its ability to attain, transport, and retain fluid is of paramount importance in terms of concrete durability. The two main types of water absorption tested in WFS concrete literature are those of immersion and absorption by capillary action. Analysis of WFS concrete subjected to water absorption tests has been collated in Table 3.

It is clear that the inclusion of WFS generally contributes to increased absorption by both immersion and capillarity; yet is often deemed tolerable up to a given replacement, with none of the referenced research considering the inclusion of WFS as unviable from an absorption perspective. Absorption increase with WFS inclusion has mostly been explained by the presence of clay, increased WFS surface area leading to inferior binding/hydration or pore structure modification and unimodal grain size leading to inferior packing. There is evidence however, of improvement in absorption with WFS through void reduction by improved packing and filler effect of WFS particles.

Guney et al. [36] evidenced a clear relationship between void ratio and water absorption, suggesting as per conventional concrete, increased void content increases susceptibility to fluid penetration. The effect of WFS replacement on water absorption is displayed graphically in Fig. 6.

The continuous linear increase in absorption with WFS replacement reported by Basar and Deveci Aksoy [51] correlates to the continuous linear decrease in compressive strength observed for the same study in Fig. 1; statistical analysis confirmed such similarities across all mechanical properties. Mavroulidou and Lawrence [22] displayed similar correlation between mechanical and absorption properties, identifying similar fluctuations in each at given replacement. Gholampour et al. [54] show a significant increase in absorption from 50 % to 100 % substitution, alongside a near identical relative magnitude of compressive strength reduction. Khatib et al. [62] also identified a direct linear correlation between absorption increase and compressive strength decrease, as well as a stronger linear relationship at longer curing periods. This result is perhaps a further reflection of WFS concrete behaviour tending towards that of control concrete with extended curing times. In summary, absorption by both immersion and capillarity increases with increasing WFS, yet such properties require further research to gain a more complete understanding of hygroscopic properties. Abrasion resistance is a key durability property, of particular importance relative to hydraulic structures. It is known that compressive strength properties are directly linked to better abrasion resistance [74], with the same results shown within WFS concretes [47]; yet

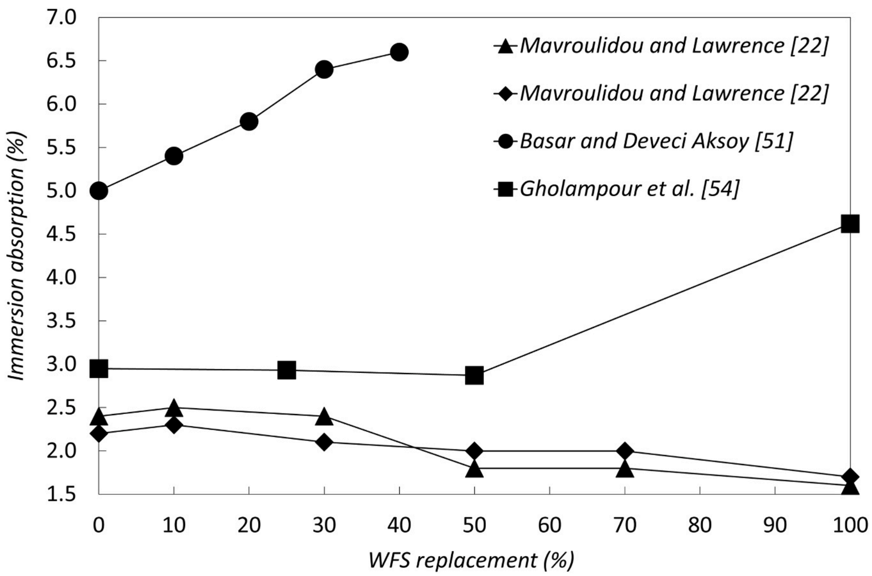

Fig. 6. Impact of degree of WFS replacement on water absorption by immersion.

Table 4
WFS concrete abrasion resistance research comparison.

Source	Testing method	WFS replacement (%)	Main findings	Authors explanation of findings
[47]	Grinding disc (BIS:1237–1980)	0–20	Wear depth improvement up to 15 % replacement, all WFS samples superior to control	WFS fineness contributing to denser matrix
[48]	-	0–25	Improved abrasion resistance with increasing WFS up to 20 %, all WFS samples superior to control	Increased density of matrix due to WFS fineness
[53]	-	0–25	Improved abrasion resistance with increasing WFS up to 25 %, all WFS samples superior to control	Increase in finer WFS particles with higher hardness index
[75]	Modified rotating cutter (similar to ASTM C944–05)	0–45*	Inclusion of WFS and fly ash reduced abrasion resistance, all WFS mixes below standard limits	-

Notes: *20–34 % fly ash as SCM.

has attracted limited research for WFS concrete. A comparison of the available literature concerning this property is presented in Table 4.

There is agreement that abrasion resistance of WFS concrete is tolerable and within respective standard limits. Most research displays continuous improvement up to an optimum replacement in the region of 15–25 %, however, replacement beyond lower percentages has not been fully tested.

Carbonation is a significant contributor to reinforcement corrosion in concrete structures, where atmospheric carbon dioxide reacts with cement hydration products, which in turn lowers the pH of the concrete medium to around 9 [57]. The lowering of the concrete pH facilitates de-passivation of the protective layer surrounding reinforcement, whereas at pH levels of above 9 such corrosion is deemed insignificant [76]. The products of corrosion can facilitate expansion, which can lead to cracking and further internal degradation. The limited data on WFS carbonation testing is compared in Table 5.

Literature is in agreement that carbonation penetration increases with WFS content, yet, the extent of penetration is highly variable, with some studies only showing suitability up to an optimum, and others deeming maximum (100 %) replacement suitable. The variation in terms of carbonation coefficient and penetration depth is evident, further displaying the individual nature of each WFS and its corresponding interaction with the concrete matrix. The primary methods used to deduce corrosion potential are that of electrical resistivity, and Rapid Chloride Penetration Testing (RCPT). There is again, limited investigation into corrosion within literature; those studies which have assessed this property are collated in Table 6.

It is clear that WFS has a highly variable impact on corrosion potential. Increased susceptibility to chloride penetration is often attributed to poor workability, creating a pervious pore structure; yet improvements are attributed to the filler effect of fine particles. Results outlined by Coppio et al. [46] are further indication of property enhancement as compared to control at extended curing periods, a phenomenon previously encountered in relation to a number of WFS concrete properties. The impact of WFS on corrosion potential is more clearly evidenced in Fig. 7.

The point at which properties begin to degrade is evident across studies, yet all display concrete of superior performance to control concrete. It may therefore be concluded that in most cases the inclusion of WFS improves corrosion resistance with values typically within 'low' or 'moderate' likely chloride penetration limits [78,79]. The range of WFS composition renders individual analysis imperative if a reasonable level of confidence in such durability properties is to be obtained.

The range of data on cyclic weather degradation in terms of freeze thaw and wet dry durability is extremely limited; relevant studies are given in Table 7.

There is obvious variation in WFS impact on cyclic exposure durability; half of all published research suggests contribution to an improvement, with the remainder indicating the opposite. As such, it is difficult to draw firm conclusions as to the influence of WFS on these specific durability properties until further studies add to the existing body of evidence in Table 7.

Despite the branding of WFS as non-hazardous waste, leaching potential still proves a topic of prime importance when considering the full life cycle of WFS concrete, a collation of current research is displayed in Table 8.

It is clear that binding WFS within a cementitious matrix is a valid way of limiting contaminant leaching, with the general consensus of Table 8 also reflected in other research; Mastella et al. [82] analysed raw WFS where low water solubility compounds such

Table 5
WFS concrete carbonation research comparison.

Source	Testing method	WFS replacement (%)	Main findings	Authors explanation of findings
[18, 52]	Similar to RILEM CPC-18	0–50	Non-linear increase in carbonation depth with increasing WFS, maximum at 50 %, tolerable at 30 %	Reduced workability with increased WFS creating pervious system, WFS carbon content reacting to form calcite
[22]	BS EN14630:2006	0–100	Increasing carbonation depth with increasing WFS at W/C= 0.45, reverse for W/C= 055. Similar performance to standard concrete	Reduced air content of W/C= 0.55 mix
[42]	RILEM CPC-18	0–60	Increasing carbonation depth with increasing WFS, all mixes deemed sufficient regarding cover	

Table 6
WFS concrete corrosion potential research comparison.

Source	Testing method	WFS replacement (%)	Main findings	Authors explanation of findings
[18]	RCPT (ASTM C1202–97)	0–50	Increasing charge passed with increased WFS, more significant beyond 30 %	Poor workability resulting in porous microstructure, impurity presence forming voids
[41]	RCPT (ASTM C1202–97)	0–20	Reduced charge passed in WFS samples, optimum at 15 %, maximum at 5 %	Filler effect of WFS creating denser matrix
[42]	RCPT (ASTM C1202–97)	0–60	Limited impact until 50 % replacement where significant increase in charge passed, all 'very low' penetration	-
[46]	Surface resistivity (UNE83988–2)	0–100	WFS initially reduced resistivity, then increased to that of control with curing	WFS metal content experienced increased conductivity; then with curing, hydration incorporated these particles into matrix
[48]	RCPT (-)	0–25	Reduced charge passed in WFS samples, optimum at 20 %, maximum at 25 %	Particle packing behaviour creating denser matrix
[52]	Electrical resistivity (-), RCPT (ASTM C1202–97)	0–50	Increasing charge passed and decreasing resistivity with increased WFS, more significant beyond 30 %	Poor workability resulting in porous microstructure, impurity presence forming voids
[53]	RCPT (-)	0–25	Reduced chloride permeability in WFS samples, optimum at 15 %	Filler effect of WFS fines, cement hydration acceleration
[77]	Rebar mass loss on immersion in NaCl, impressed current, half-cell potential (ASTM C876)	0–40*	Improved mass loss and corrosion resistance as compared to control samples up to 30 % WFS, delayed corrosion initiation in WFS samples	Filler effect of WFS fines, increased silica content contributing to retaining alkalinity at steel

Notes: *HCl treated WFS.

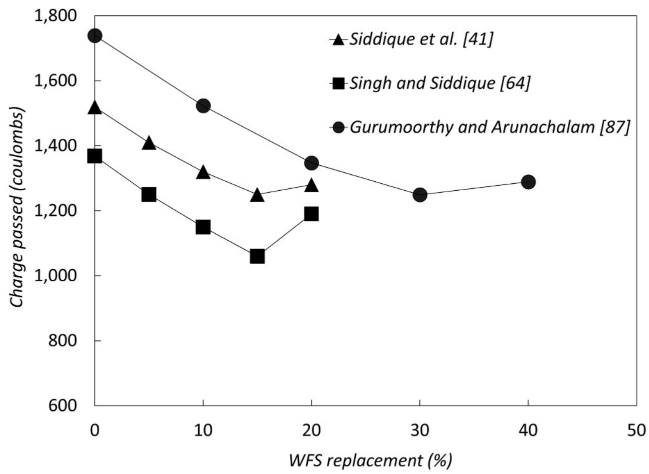

Fig. 7. Impact of degree of WFS replacement on 28-day charge passed as an indication of corrosion resistance.

as formaldehydes were shown, suggesting that once bound in a cementitious matrix, such compounds may become inert with reduced toxicological impact. Other authors have also outlined favourable environmental performance relative to leaching from controlled low strength materials with the addition of WFS [83]. There is also evidence that such a process could be further optimised; Reddi et al. [84] determined that alternative binder material often performed better in WFS contaminant leaching tests than Portland cement, with Navarro-Blasco et al. [85] suggesting calcium aluminium cement may improve heavy metal retention.

It is clear that the variation in terms of leachate concentration and compliance is vast, and the range of data limited, particularly related to the end-of-life scenario. For the most part however, relative consistency is shown in terms of concentration reductions once WFS is bound within a cementitious matrix. Such a suggestion lends itself towards the incorporation of such waste within concrete as a preferred option in terms of relative environmental impact; provided adequate durability is attained and life cycle considered. The fact that all aforementioned research into leaching is related to that in the aqueous phase is noteworthy, and the authors therefore suggest further research into the potential for volatilisation of gaseous compounds in air to strengthen the understanding of WFS leaching under variable conditions. This being said, there is almost certainly less susceptibility to leaching in air given the visual evidence of physical binding of contaminants to grains [33,35,67,73], and the necessity for largely increased temperature to remove contaminants; two clear mass losses at 100 °C and 400 °C under TGA have been evidenced by multiple authors [67,86], corresponding to water and

Table 7
WFS concrete freeze thaw and salt scaling research comparison.

Source	Testing method	WFS replacement (%)	Main findings	Authors explanation of findings
[36]	Freeze thaw (ASTM C666)	0–15	Magnitude of compressive strength reduction similar to control, all WFS samples within ACI318–99 limits	Clay particles reducing bond strength between aggregate and cement paste
[41]	Salt scaling (ASTM C672)	0–20	Improved scaling resistance with WFS content, 15 % optimum	WFS fines acting as packing material creating denser matrix
[60]	Freeze thaw (EN12012:2007)	0–15***	All WFS samples inferior to control	-
[68]	Freeze thaw (ASTM C1262)	0–35**	Largely inferior freeze thaw resistance in WFS samples	Presence of clay particles imparting weak sliding zones around grains
[75]	Freeze thaw (ASTM C666), salt scaling (ASTM C672)	0–47*	Excellent freeze thaw resistance in WFS samples, similar scaling resistance up to 20 % WFS, poor beyond 43 %	Use of WFS alongside fly ash

Notes: *25–40 % fly ash as SCM, air entrainment used for freeze thaw samples, ** 0–25 % fly ash as SCM, ***0–25 % coal cinder as coarse aggregate replacement, 5 % SF as SCM.

Table 8
WFS concrete leaching research comparison.

Source	Testing method	WFS replacement (%)	Raw WFS findings	Cement bound WFS findings	Authors explanation of findings
[30]	Leaching (ABN NBR1006/2004)	0–100*	Al concentration exceeds limits	Leachate fully compliant at 100 % WFS as a non-hazardous class II or inert class II B waste	Heavy metal leaching controlled through reactions between CSH, carbon dioxide and portlandite; impacting solubility and immobilising heavy metals
[51]	Leaching (TS EN12457–4:2004)	0–40	Non-compliant with Class III Waste Acceptance Criteria in terms of DOC, Cr, Ni, Zn, F, TDS, and TOC	Compliant with same criteria at a range of pH levels	WFS binding into solidified product can immobilise many raw WFS contaminants
[67]	Leaching (NBR10005:2004 / UNE-EN12457–4:2003)	0–50***	Sulphate, chloride, fluoride, heavy metals and DOC within limits, high surface resin WFS displayed non-compliant phenol levels	High leaching rates of crushed mortar, suggesting end of life issue	Phenol release intensified once part of cement matrix through pH increase
[80]	Leaching (D.M.05/02/ 1998 similar to ASTM C1220 / ISO6961)	0–30*	-	Compliant with Italian water limits aside from Al. Low heavy metal content and alkaline solution throughout.	-
[81]	Leaching (ASTM D3897 variations)	0–20**	-	Increased Ni, Pb and Cr compared to control samples. Certain metallic concentrations above WHO drinking water limits and ground water standards	Metal content relative to in-foundry casting material

Notes: *Mortar testing, **Fresh concrete testing, ***Broken mortar testing.

Table 9
WFS concrete sulphate resistance and aggregate reaction research comparison.

Source	Testing method	WFS replacement (%)	Main findings	Authors explanation of findings
[30]	Alkali-aggregate reaction (NBR15577–4)	0–100	Increased expansion in WFS samples, maximum at 50 %	Denser, less porous concrete reduced significant ASR
[52]	Sulphate resistance (-)	0–50	Reduced sulphate resistance with increasing WFS, significant beyond 30 %	Presence of sulphur in WFS increasing solution strength and enhancing ettringite formation
[60]	Sulphate resistance (EN12370:2001)	0–15**	Largely improved sulphate resistance in WFS samples, optimum at 5 %	-
[87]	Sulphate resistance (ASTM C1012)	0–40*	Improved sulphate resistance in WFS samples, optimum at 30 %	-

Notes: *HCl treated WFS, **0–25 % coal cinder as coarse aggregate replacement, 5 % SF as SCM.

Table 10
WFS treatment research comparison.

Source	Treatment method	Intended treatment impact on WFS	Treatment impact on WFS	Treatment impact on WFS concrete / mortar	Other findings	Authors explanation of findings
[19]	Water washing*	Property optimisation for use in cementitious materials (alkaline ions, heavy metals)	-	Improved mechanical performance, compressive strength recovery at longer curing periods, hydration acceleration due to alkaline ions eliminated	-	-
[44]	Fungi synthesised silver nanoparticle treatment (Aspergillus terreus)***	Removal of heavy metal contaminants	Black to brown colour change, pH and metal contaminant reductions	Improved compressive and tensile strengths	-	Deposition of silver nanoparticles within pores
[67]	NaOH washing**	Reduction in phenolic content to improve mortar properties	Reduced Ba, Cd, Mo, Se, Zn, sulphate, fluoride, chloride, DOC, and phenols. Increased Cu, Sb and pH	Improved compressive and flexural strength, reduced absorption and void ratio, mostly reduced leachate concentrations from broken mortar	-	-
[81]	Fungal treatment (Aspergillus)***	Biomineralisation of WFS to improve concrete properties, reduction in heavy metal contaminants	Reduction in heavy metal leachate, compliant with WHO drinking water and Ground Water Standards	Further reductions in metal leachate, increased compressive strength, reduced porosity	-	Formation of calcified filaments and biominerals
[88]	Wet and dry mechanical agitation*	Property optimisation for foundry reuse (fineness, acidity, clay and metal content)	Significant metallic contaminant reductions	-	Dry method most efficient	-
[90]	EDTA–NaOH–NH3 washing*	Removal of potentially toxic elements	Degradation rates of 98 % Cu, 81 % Pb, 83 % Sn, 50 % Zn	-	Optimised at three 3 h washes	-
[91]	Water and H_2SO_4 washing***	Removal of surface contamination (carbon, clay, metals, organics, residual binder) to improve mortar properties	Colour change from black to brown, reduced SG, bulk density, absorption, SiO_2, MgO, TiO_2, and CaO. Increased Na_2O, Al_2O_3, and Fe_2O_3	Improvements in compressive strength, absorption, sorptivity, and chloride penetration	Similar results for both treatments, but superior results from H_2SO_4 wash	-
[99]	Bacteria treatment (Burkholderia)**	Biodegradation of phenolic compounds	Degradation rates of 97 % phenol and 100 % m/o-cresol, reduced acidity and bacterial toxicity	-	Environmentally and cost effective	-
[100, 101]	Mechanical, thermal, and compressed air agitation*	Property optimisation for foundry reuse (fineness, acidity, clay/binder content)	10 % residual binder reduction	-	Mechanical attrition preferred over fluidised bed due to operational costs	-
[102, 103]	Fungal treatment (Aspergillus / Eupenicillium crustaceum)***	Biomineralisation of WFS to improve concrete properties	-	Increased compressive strength and CSH production, reduced absorption and porosity	-	Deposition of fungal biomineral within pores, formation of calcium oxalate

Notes: *Green WFS, **Chemically bound WFS, ***Unknown WFS.

unburned carbon respectively, highlighting the requirement for increased temperature for any volatilisation in air.

Sulphate resistance is vital to long term durability, particularly when considering potentially reactive aggregates, yet it remains perhaps the least investigated WFS concrete durability property. A comparison of available research is shown in Table 9.

There is a direct split between relative improvement and degradation of properties with the inclusion of WFS. Such contradicting results suggest little other than a further indication of the variability of WFS performance, and a requirement for further testing.

2.4. WFS pretreatment for performance optimisation

WFS treatment as a means of improving properties and reducing contamination has received significant attention by both concrete researchers, and the foundry industry. For foundry industries, treatment can improve properties for subsequent reuse and extension of service life or reduce contamination for more efficient disposal; for concrete research, the aim can also be to reduce contamination, yet is typically to optimise performance of WFS within a cementitious composite.

The impact of such on chemical and physical properties has the potential to provide a contribution towards standard compliance and normalised application; yet is hindered by the expensive and time-consuming nature of many treatment processes, particularly when attempting to scale up. Prior to the reported impact of various treatments in literature, it would prove beneficial to discuss the intention and theoretical basis of each to maximise value for future research.

Some of the more traditional treatment methods are that of mechanical and thermal agitation, both of which aim to remove contaminants and binder material from WFS grains. Mechanical reclamation utilises attrition and mechanical scrubbing of grains to removes impurities, whereas thermal treatment employs heat from kilns or furnaces to combust binders and contaminants [88].

Washing treatment also typically intends to purify WFS and reduce contamination levels and may be conducted with a range of washing solutions. The basis of water washing is to remove surface level, non-chemically bound contaminants that contribute to a reduction in WFS purity. Acidic solutions contribute to the degradation of bentonite material [89] and may aid with removal of heavy metals and toxic elements, specifically by chelation [90]; consequently, acids have been used with the intention of removing residual binder and surface contamination [91]. In terms of alkali solutions, there is limited research into the associated mechanisms for application to WFS, but it has been suggested that basic conditions may contribute to overall dissolution of metallic ions [90], possibly contributing to a reduction in heavy metal concentrations.

Another common pretreatment is the exposure of WFS to bacteria or fungus. The theoretical basis of such is often to promote biomineralization in the form of carbonates, oxalates or similar precipitates. Such precipitation has been directly applied to cementitious matrices in improving mechanical strength [92], durability properties [93], and crack healing [94], but perhaps most importantly in relation to the current study, may also contribute to removal of toxic or heavy metals in contaminated media or environments [95,96]. Similar biological treatment by use of Burkholderia bacteria has also been established as a methodology for direct degradation of phenolic compounds [97–99].

A comparison of WFS treatment research is shown in Table 10.

It appears that all treatments assessed yield positive impacts in improving WFS or WFS cementitious composite properties through either contamination reduction, or physical property improvement. Treatment by biological techniques has seen relative success, with other review articles also deeming biomineralization a successful methodology for WFS concrete improvement [104]. Chemical treatment by means of acid or alkali washing is a process that is somewhat scalable and evidently successful in improving WFS composite properties. Hydrochloric acid treatment has been investigated with the aim of removing iron and enriching silica [77,87,105], displaying improved compressive strength, CSH spread, sorptivity, and resistance to chloride, acid, sulphate, marine environment and corrosion as compared to control samples; yet there is limited comparison to samples of untreated WFS, and hence the degree of impact of treatment proves hard to ascertain.

As an alternative to treatment, Reddi et al. [84] investigated the use of SCMs as a means of stabilising phenolics within WFS, where it was determined that binding with FA and cement can prove cost effective solutions. Such outcomes, along with the suggestion that cement-bound WFS is generally less susceptible to leaching of harsh chemicals [51,82,83], challenges the need to pretreat WFS prior to inclusion within concrete. Many of the aforementioned treatment processes are not only costly, but also time consuming; often proving difficult to implement on an industrial scale without additional infrastructure and storage investment. In summary, the pretreatment requirement should be considered as part of the cost and life-cycle analyses.

2.5. WFS in combination with SCMs

The use of SCMs within a mix using WFS as fine aggregate replacement has the potential to alleviate some of the shortcomings associated with WFS inclusion, whilst further reducing the concrete's embodied carbon. WFS can be used in combination with any

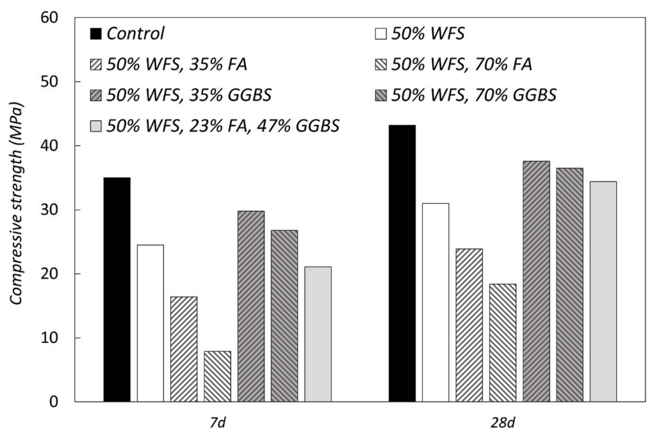

Fig. 8. Assessment of SCM impact on WFS concrete compressive strength, data obtained from Gholampour et al. [54].

cementitious material [20] and many researchers have suggested further investigation into such possibilities, yet such research is limited and often reveals little in terms of the extent and explanation of SCM impact.

In order to quantify the relative effect an SCM has on a WFS concrete, comparison to WFS samples without SCM and control samples is required. Such testing is scarce in literature; most WFS SCM research retains a consistent percentage of cement replacement or only provides comparison to an SCM sample without WFS. This, along with variation in experimental and design variables, renders direct comparison between many SCM WFS studies challenging; particularly when considering the significant variation of WFS product as standard.

Gholampour et al. [54] have analysed the relative impacts of FA, GGBS, and combinations of both on physical, mechanical and durability properties of WFS concrete; a compressive strength comparison of such is displayed in Fig. 8.

In line with many other studies previously assessed the compressive strength reduces with WFS inclusion, despite the use of SCMs. The shortcoming of current research in this area is the lack of long term compressive strength data, particularly considering the pozzolanic nature of SCMs and the potential for further strength gain with time. It is evident that a high proportion of FA is largely detrimental to compressive strength at all curing periods, showing reductions of 67.8 % and 40.6 % compared to OPC WFS samples at 7 and 28 days curing respectively. Such behaviour is somewhat anticipated however, given the use of a replacement level well beyond that recommended by construction standards. Moreover, the same effect was shown at the lower dosage of 35 % FA replacement but to a lesser degree.

In contrast, GGBS mixes displayed improvements in compressive strength relative to the WFS sample with 100 % OPC; the most significant at 35 % replacement where 21.6 % and 21.3 % increases were shown at 7 and 28 days curing respectively. The FA and GGBS blend also showed strength improvements in the region of 11 % at 28-day curing, overcoming the poor results of FA use alone at the same age. Consistent with previous investigations into mechanical properties, similar trends were observed in terms of MOE and tensile properties. WFS concretes containing FA tended to show lower MOE, with increased water absorption and workability, whilst GGBS mixes tended to show the reverse. Such research evidences the impact that SCM material, particularly GGBS and blended mixes, can have on improving WFS concrete properties.

Other authors have shown favourable results substituting a consistent 15 % GGBS, with improved mechanical properties up to an optimum WFS replacement of 30 % [106]. Similar testing was conducted at the same constant GGBS replacement, yet with largely different outcomes [107]; reduced compressive strength and increased water absorption were evidenced with increasing WFS.

More favourable results with FA replacement have been evidenced by Reshma et al. [108], with improvements in workability, ultrasonic pulse velocity, compressive, tensile, and flexural strength up to an optimum of 30 % WFS. Such improvement was relative to a FA sample with no WFS and explained by increased silica and alumina in both WFS and FA. Other researchers have also tested samples at consistent 30 % FA replacement, coming to similar conclusions in terms of improved strength properties at all curing periods, but this time displaying optimum properties at 60 % WFS [109]. Both studies displayed compressive strengths in the region of 40 MPa at 28 days. Higher quantities of FA have been tested alongside WFS at 50 % cement replacement [110] where improvements were shown in terms of water absorption and chloride penetration, with an optimum strength value displayed at 15 % WFS. Detailed analysis of WFS concrete alongside FA [68,75] has previously been analysed in the current publication, with such research yielding comparable durability and mechanical results to control samples, yet proving difficult in terms of distinguishing the impact of FA to that of WFS.

SF has also been tested alongside WFS, where a constant 5 % was replaced [60], providing evidence of the compatibility of SF and WFS with improved porosity and salt resistance, as well as similar values of absorptivity, density, and compressive and tensile strength. WFS has also been used in combination with Portland Pozzolana Cement [49,64,65,106,111], and unconventional SCM such as wood ash [112], sugar cane bagasse ash-eggshell lime [113], and glass waste [114]. Again, it is difficult to distinguish the relative impact of binder and WFS content in these studies due to variations in mix constituents and designs.

Dual fine aggregate replacement with both WFS and copper slag, as well as simultaneous coarse aggregate replacement using recycled aggregate and sintered FA have both been investigated alongside SCMs such as GGBS, Alccofine and MK [115]. Ternary blend compatibility was displayed with superior compressive strength properties displayed as compared to control samples. Of recent, WFS combination with an alkali-activated binder continues to receive research attention, with many studies rendering such not only feasible but beneficial in terms of both sustainability and engineering performance [116–119].

There are a number of studies assessing the use of WFS in SCC mixes, where it is worth acknowledging the integral role of alternative binders as a means of achieving desirable properties. SCMs such as FA [120–128], SF [121,129,130], Rice Husk Ash [131,132], MK [133,134], and other mineral additions [122,129,130] have been successfully incorporated into mix designs.

It is clear that there is a significant lack of data allowing relative quantification of SCM impact on WFS concrete properties. Given the potential outlined for enhancement of both engineering and environmental performance, it proves necessary to further investigate such dual replacement as a feasible sustainable concrete solution.

2.6. WFS concrete life cycle and economic analyses

Limited studies present a quantification of environmental impact and economic viability of WFS concrete, despite its integral role in assessing the feasibility of WFS concrete implementation in practice. Even in the case a superior product were developed, scaling would prove impossible should the associated costs outweigh other benefits. It is imperative to recall that the main aim of WFS concrete is the reduction in quantity of raw material extraction, mix embodied carbon, and waste disposal to landfill. The quantification of environmental impact therefore becomes critical; yet the scarcity of publications in this area evidences the difficulty in conducting such an exercise, often owing to complications in obtaining sensitive business- critical information regarding WFS.

Table 11
Summary of WFS impact on concrete properties.

Concrete property	*General impact of WFS on concrete property*	*Maximum WFS replacement evidenced with 'reasonable' results**
Workability	Decreases	100 % [22,54]
Hardened density	Decreases (minimal)	100 % [54]
Compressive strength	Inconclusive	100 % [22,30,46]
Tensile and flexural strength	Inconclusive	100 % [22]
Drying shrinkage	Increases	50 % [35]
Porosity	Increases	100 % [46]
Water absorption	Increases	100 % [22,46]
Abrasion resistance	Increases	45 % [75]
Carbonation resistance	Inconclusive	100 % [22]
Corrosion resistance	Increases	100 % [46]
Freeze thaw and salt scaling resistance	Inconclusive	20 % [41]
Leaching potential	Decreases	100 % [30]
Sulphate resistance	Inconclusive	40 % [87]

*It is clear that the term 'reasonable' is subjective and application dependent, hence the chosen maximum replacement values are identified as compared to the individual studies control samples and not across WFS literature as a whole. Typically this will mean no more than a 30 % reduction in values.

In terms of economic impact, research has provided detailed analysis on variables associated with in-foundry reclamation [88,100,101,135] with focus on financial implications of treatment relative to disposal and purchase of raw material. The market price of raw material, as well as foundry size are significant factors in terms of economic feasibility; Zanetti and Fiore [88] displayed variation in market price from 0.01 €/kg in Belgium and The Netherlands to 0.04 €/kg in Italy, leading the author to recommend bespoke construction applications in different regions.

A feasibility assessment of WFS concrete has been conducted where long term durability as a function of WFS purity was highlighted as being a key contributor to economic feasibility [132]. Basic cost comparisons have evidenced economic feasibility by pricing individual mix component quantities in comparison to those of a standard mix, where savings of 7.5 % at 20 % WFS [53], 4.7 % at 45 % WFS [107], and 9.5 % at 100 % WFS [73] were shown; with the latter also highlighting the elimination of WFS disposal costs through reuse. Notably, in these cases, although concrete performance is often negatively impacted, additional cement/admixture is not required to improve or retain performance to standard. Were this the case, economic feasibility may be jeopardized; it is therefore critical that the performance of WFS concrete is suitable for the specification or application in question without the need for significant mix alteration. Mavroulidou and Lawrence [22] highlighted secondary attrition as a cost-effective solution for producing a quality WFS product, which will have already been conducted during attempted reclamation within the foundry. As such, the use of WFS in concrete incurs no additional cost aside from transportation, whilst simultaneously reducing landfilling expenses for foundries. It was determined that in the context of a small UK foundry, £ 2000 per month may be saved. It is likely that in many cases foundries would pay a premium for WFS reuse given the current costs associated with landfilling, providing a negative cost for concrete manufacturers. This, as well as cost associated with transport of WFS from foundry to batching plant, regional variability, foundry size and scalability of operation should all also be accounted for within such an analysis.

The only paper to assess LCA specifically in the context of a standard WFS concrete showed significant improvements as compared to conventional concrete [136]. Reductions were displayed in terms of global warming potential, abiotic resource depletion, acidification potential, eutrophication potential, photochemical ozone creation potential and net energy consumption via a reduction in cement and fine aggregate demand; environmental impacts were reduced to about 85 % of those of conventional concrete. Notably, the point at which the process proves unsustainable relative to delivery distance remained well within a standard delivery range for all environmental variables.

Environmental assessment has also been conducted on the use of WFS as a geotechnical material [137] where similarities may be drawn in the reduction in raw material and environmental impact by landfilling; as per data from a different source [138], the use of WFS as a replacement for quarried sand could save 81 MJ of embodied energy and 5.1 kgCO2e per ton. Tangadagi and Ravichandran [139] investigated WFS SCC LCA using the EcoInvent 3.2 database: evidencing potential for reduced global warming potential, energy requirement, and other environmental variables through use of treated WFS as fine aggregate replacement. A number of authors have also shown relative environmental success in conducting LCA on alkali-activated materials with the use of WFS [116,140].

Undoubtedly there is scope to market the use of WFS in concrete in terms of both financial and environmental benefit, should data be collated and presented to industry in a more detailed and case specific format. It is evident however, that there is a severe lack of accurate environmental performance data, highlighting the requirement for detailed LCA with information from both foundries and concrete manufacturers.

Finally, it is worth noting recent developments in advanced applications of WFS concrete; such research is vast and could warrant a literature review of its own, hence is only briefly referenced herein. Applications such as self-compacting, fibre reinforced, lightweight, autoclaved aerated, permeable and geopolymer/alkali-activated concretes have seen significant research success, evidencing compatibility with WFS as a means of improving workability, mechanical and durability properties, reducing structural dead load, facilitating improved drainage, and limiting cement consumption, respectively. A growing area of research of late has also involved the use of AI and machine learning to predict mechanical properties and aid in improving the efficiency of physical research and mix design. The scope of such outlines the global and interdisciplinary nature of WFS concrete research, and its growth towards regulated industrial application.

3. Conclusion

It is clear that the concept of WFS as a fine aggregate replacement in concrete is becoming increasingly popular, with ambitions to contribute towards a reduction in both natural resource depletion and unsustainable waste disposal. In the future, this will not only be an economic driver for foundries, but also an environmental and legislative driver for construction and manufacturing industries alike, as we work to preserve our planet for future generations. It is clear that there is significant variation in terms of chemical, physical, fresh, mechanical, and durability properties; even in areas where trends appear to show stronger relative correlations. It proves extremely difficult to draw firm conclusions since there is always conflicting evidence; nonetheless, an attempt has been made to highlight general trends in terms of relative impact of WFS inclusion on concrete properties in Table 11.

The significant variation in relative impact on properties is clear, as is the largely inconclusive nature of cumulative research. Those properties deemed inconclusive are due to significant conflicting conclusions, lack of investigation, or a combination of both. Variation in results is evident in the fact that those properties which are possible to draw a generalised conclusion, often retain a contradictory result in terms of the maximum replacement displayed with reasonable results. For example, workability is known to decrease with increasing WFS replacement, yet Mavroulidou and Lawrence [22] have shown improvements at 100 % substitution.

Mechanical properties are deemed inconclusive due to largely conflicting results; such properties are better described by one of four generic trends outlined previously. Resistance to carbonation, abrasion, freeze thaw and sulphate have not only displayed conflicting results, but have not received sufficient investigation to draw firmer conclusions. The negative impacts of WFS inclusion may be summarised by a reduction in workability and hardened density, as well as increased drying shrinkage, porosity and water absorption. Literature has suggested that resistance to corrosion and leaching potential may be improved by incorporating WFS into the concrete matrix.

The nature of WFS is such that its subsequent properties post processing are as varied as its manufacturing procedures, hence highlighting the imperative nature of individual analysis of both the sand itself, and the ensuing concrete properties. Despite this increased workload, inspiration may be taken from the widespread use of FA within the concrete industry despite the fact that it too proves largely variable in terms of physical, chemical and mechanical properties [141]. Such discrepancies complicate generalisation in a similar sense to that of WFS, perhaps providing evidence that such technologies can and do become the norm if both the environmental and financial stimuli are present. Despite such variation, there is a consistent display of acceptable results relative to all properties until a given replacement percentage; it is widely understood that in all cases, at least some level of WFS replacement is viable.

Both the use of pretreatment, and combination with SCM have been highlighted as successful methodologies for optimising WFS concrete performance. Biological, chemical and physical treatment methodologies have all seen relative success in terms of improving the properties of either WFS itself, or an ensuing cementitious composite. Environmental assessment of such will aid with confirming the necessity of treatment, particularly given evidence suggesting the combination of WFS with SCM may provide sufficient property enhancement. WFS has proven compatible with a wide range of SCMs, and combining such provides a promising avenue for optimisation of engineering performance.

The economic viability of WFS concrete has been clearly demonstrated by comparative assessment to standard concretes, where in all cases, potential for savings from a concrete manufacturing perspective were evidenced. There is clearly also scope for significant savings from the foundry perspective, given the reduction or potential elimination of landfilling costs. Similarly, environmental benefit has been clearly evidenced through use of LCA, reinforcing the widely circulated fact that WFS concrete proves more sustainable than that of a conventional mix.

4. Research significance

It has been made abundantly clear that there are significant gaps in the knowledge of WFS concrete of which further research can help fill and consequently contribute towards standardisation. In particular, a deeper understanding is required in terms of bonding and ITZ characteristics, long-term durability, chemical and contamination compliance, pretreatment, and quantification of relative impact of SCM alongside WFS.

The mapping of regional and national WFS composition and quality, and its relative impact on WFS concrete engineering properties would be largely beneficial in providing a database for consultation. Such a repository would allow designers, manufacturers, construction professionals and policymakers to work towards consistent and standardised implementation of WFS concrete.

A more holistic analysis of the wider economic business model would prove valuable for scaling up, accounting for regional variation, local market prices, application, specification, transport and scale of operation. Similarly, additional studies evidencing the variation in detailed and case specific LCA will prove critical in further highlighting the environmental benefit of incorporating WFS within concrete and optimising the WFS concrete manufacturing process.

Despite the challenging nature of scaling to industry, literature has provided evidence that the use of WFS as a fine aggregate replacement within concrete not only has potential for compatibility in terms of engineering properties; but could also prove environmentally, legislatively and economically feasible for investors. Should such research be collated successfully, it would provide sufficient evidence in all major aspects required to propose the development of appropriate material standards and implementation on an industrial scale.

CRediT authorship contribution statement

Riccardo Maddalena: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Joseph Pugh:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Diane Gardner:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Riccardo Maddalena reports administrative support, article publishing charges, equipment, drugs, or supplies, and travel were provided by Cardiff University. Joseph Pugh reports financial support was provided by Knights Brown. Joseph Pugh reports financial support was provided by Carbon Upcycling Technologies. Joseph Pugh reports financial support was provided by Weir Group PLC. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data available at the link https://doi.org/10.6084/m9.figshare.30611300

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Glossary

AI: Artificial Intelligence
ASR: Alkali-Silica Reaction
CSH: Calcium-Silicate-Hydrate
DOC: Dissolved Oxygen Content
FA: Fly Ash
GGBS: Ground Granulated Blast Furnace Slag
ITZ: Interfacial Transition Zone
MK: Metakaolin
MOE: Modulus of Elasticity
OPC: Ordinary Portland Cement
SCC: Self-Compacting Concrete
SCM: Supplementary Cementitious Material
SF: Silica Fume
TDS: Total Dissolved Solids
TGA: Thermogravimetric Analysis
TOC: Total Organic Carbon
W/C: Water Cement Ratio
WFS: Waste Foundry Sand
WHO: World Health Organization
Note: the article refers to ton and tonnes as different units, to reflect the original meaning of the study or source referenced.