


Review

The Production of Sustainable Concrete with the Use of Alternative Aggregates: A Review

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Abstract: The concrete industry is a core element of the building sector, but it has to deal with the increasing attention on the environmental issues related to the production process: increasing energy efficiency and the adoption of alternative fuels or raw materials represent the most relevant solutions. The present work analyses physical, mechanical, and environmental performances of concrete incorporating residues derived from four main sources (construction and demolition waste, residues from waste treatment, metallurgical industry by-products, and others), as substitutes of either fine or coarse aggregates. Fine aggregates showed the highest number of alternatives and replacement level, with the relevant impact on concrete properties; coarse aggregates, however, always reach a complete replacement, with the exclusion of glass that highly affects the mechanical performance. Construction and metallurgical industry categories are the main sources of alternative materials for both the components, with ceramic and lead slag reaching a full replacement for fine and coarse aggregates.

Keywords: green concrete; waste management; compressive strength; physical properties; environmental compatibility; circular economy

1. Introduction

Concrete still represents one of the most relevant and used materials in the building industry, as it can be considered “the second most consumed substance on Earth after water” [1]. The production process is related to a significant carbon footprint, around 850 kg of CO₂ emitted per ton of clinker [2], mainly due to the production of cement that requires a large quantity of resources, both in terms of energy and raw materials. Recommendation from the International Energy Agency (IEA) [3] include the increase in energy efficiency and the use of alternative materials, either fuels or raw materials, as the main means to decrease the environmental impact of concrete products. Investigations [4] highlight that the building sector offers the largest cost-effective greenhouse gas mitigation potential. From this point of view, aggregates play a core role as they account for about 80% to 85% of a typical concrete mixture and are responsible for an unsustainable local natural resources consumption [5]. Sand and gravel are the main resources extracted for aggregates production and traded by volume causing river

deltas and coastlines erosion. The use of substitutes and alternative materials is a suitable mean to prevent or reduce river and marine ecosystems damage [6].

Aggregates play a role in defining concrete compressive strength. They are usually divided into coarse and fine aggregates, with a diameter less than 4.00 mm. The different quality and kind of aggregates determine a different durability and workability that affect the concrete; great attention is given to avoid any chemical that can cause deterioration. The size of the aggregate depends on the final use of concrete and influence materials proportions: if the aggregate diameters are larger, a smaller quantity of cement and water is needed. Crushed stones, sand, rock quarries, and gravel are the most common materials used as aggregates, while recycled concrete and marine aggregates represent a possible, uncommon alternative [7,8].

The possible impact of alternative materials depends on the construction industry size. The building construction economy has shown a slightly recovery in the last years: according to the Italian Technical and Economic Association of Precast Concrete (ATECAP) [9] report, the concrete production in Italy is marginally increasing, moving from 25.3 Mm³ in 2015 to 27.3 Mm³ in 2017 [10], a trend confirmed by the Italian Association of Building Contractors (ANCI) [11,12]. The European production of aggregates increased around 2.5% since 2015, with Russia as the largest producing country with 592 Mt in 2016 [13].

The integration of alternative materials help both saving natural resources and reducing waste disposal by incorporating urban and industrial wastes into concrete, according to the concept of circular economy [14]. The evaluation of the environmental benefits led by the use of recycled materials in common building elements is usually carried out by a Life Cycle Assessment in terms of primary embodied energy and greenhouse gas emissions, considering a “cradle-to-gate” approach [15]. Waste reduction policies promoted at international levels could reduce this strategy in the long terms [16,17]. Last data from the Italian Technical and Economic Cement Association (AITEC) sustainability report [18] show that Italy is still far from European average value of 40% [19], underlying the need for a higher information and engagement for producers and stakeholders.

Incorporation of more alternative and sustainable raw materials from suitable waste streams is the future challenge of the concrete industry. While common production fuels can be replaced by biomass or other kinds of wastes [20], both part of fine and coarse aggregates can be made of recycled materials like scrap tyres, glass, and foundry sands, but this strategy is limited by technical issues and national regulations. The substitution of fuels and raw materials with alternative materials represents an important contribution to the circular economy, as it guarantees a feasible solution to waste management: concrete is relevant for the implementation of circular economy plans in the building sector as the most used 100% recyclable building material [21–23]. According to the cement sustainability initiative and the European Cement Research Academy (ECRA), the average substitution rate of concrete components with waste and by-products in Europe reaches more than 60% for an industry sector and up to 95% as a yearly average for single cement plants [24,25].

To properly promote the integration of waste materials in concrete, sustainable practices and an increasing demand represent the most relevant driving factors [26,27]. Alternative materials are a suitable answer to the rising cost of raw materials and the consumption of natural resources [21]. Their contribution to sustainable development comes together with specific effects on the performances of produced concrete [28]. Looking specifically to aggregates, use of alternative materials must consider the effect on both mechanical properties and durability, related to porosity and water absorption, as the most affected parameters: final specimens must comply technical requirements in terms of resistance. The present review analyses physical, mechanical, and environmental performances of the both fine and coarse aggregates incorporating wastes from four main sources: (i) construction and demolition waste, (ii) residues from waste management treatment, (iii) metallurgical industry by-products, and (iv) other by-products that does not fit in any previous sector. The aim is to provide an extensive review of possible alternative aggregates and the effects of the substitution on the characteristics of the final concrete.

2. Methodological Approach

Scopus and Google Scholar databases were the main sources for the bibliometric research, as two of the most common and wider online sources, to get transversal results on different kinds of waste. Keywords such as “green concrete”, “alternative sustainable coarse aggregate”, or “alternative sustainable fine aggregate” have been used and the results have been crossed with key terms like waste and recycled. The research focused mainly on works published in the last 10 years. The first step of the research was a preliminary screening of the found articles and reviews on source materials. We set the main categories of source materials, a second search was performed, looking for articles and studies on properties and performances of concretes made with a mix design that includes waste materials. The review is based on around 120 articles that have been divided into the four categories of wastes analysed. For each suitable alternative material, a brief description of its origin and/or composition, the stabilization methods, when needed, and the maximum replacement level detected is given. Then, physical and mechanical properties and environmental compatibility are described for each possible substitute. As mechanical properties strictly depend on target performance, values of reference concrete (RC) are reported.

3. Results

Aggregates are one of the easiest components to substitute in mix design. The classification on fine and coarse aggregates strictly depends on the diameter of the component: the most common fine aggregates in RC are sand or crushed stone. Coarse aggregates play a role in determining the final strength of concrete composite. The increasing demand of such components for the concrete industry is depleting natural resources, so alternative solutions must be found to substitute them in the production process. The integration of recycled wastes and by-products in concrete is a sustainable alternative for the disposal of such materials, generally directed to landfills or incinerators: municipal solid waste incineration (MSWI) ashes and metallurgical industry by-products represent the most hazardous wastes, in terms of possible environmental impact and quantity, that can be used as aggregate in concrete. Recycled aggregates are another relevant option, embodying a possible closed-loop circular economy example in the building sector. Looking at the concrete components, fine aggregates are the easiest element to replace in terms of number of alternatives. Coarse aggregates, as shown in Figure 1, theoretically can always reach a complete replacement, with the exclusion of glass that highly affect the mechanical performance, but legislations limit a full substitution to few countries. Construction and metallurgical industry categories are the main sources for alternative materials for both the components, with ceramic and lead slag reaching a full replacement for both fine and coarse aggregates. In addition to lead slag and ceramic, blast furnace slag and glass are the most versatile as possible substitute of both kinds of aggregates. Replacement levels are reported in Figure 1. Looking to percentages, aggregates are fully replaceable, and they mainly must provide mechanical resistance to the paste and a chemical compatibility with other concrete components. Quarry dust and incinerator sewage sludge ash (ISSA) for fine aggregates, and glass for coarse ones, are the only alternative materials with a replacement level below 50%, due to their high impact on the mechanical performance of concrete.

3.1. Construction and Demolition Wastes

A possible building waste to recover in the concrete industry is ceramic waste. It can replace sand in mix design. An increasing amount of the waste ceramic content proportionally with reduces the workability for Portland cement concrete. However, the presence of fly ash (FA) in concrete with ceramic waste guarantees a good workability even with a complete replacement of sand. The FA influences the overall performance: without FA, the compressive strength drops down over a 50% replacement level, due to the angular shape of the ceramic particles that reduce the workability. FA concrete instead has shown the opposite behaviour [29]. Looking at building industry, a natural substitute of sand can be granite quarry dust. As a waste of granite production, this dust is “a felsic

crystalline rock with interlocking texture and visible mineral grains” [30]. Available with a particle size lower than 5.0 mm, granite dust is perfectly suitable as fine aggregates. Despite a complete replacement being achievable for structural-related use, 50% has been suggested as the maximum replaceable share [31].

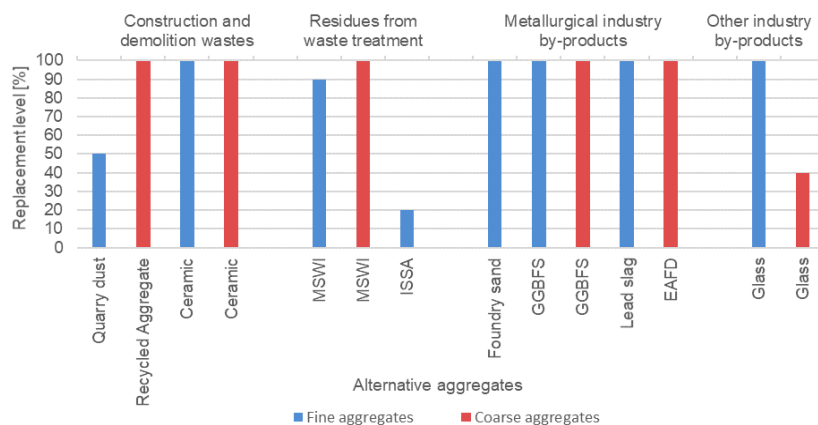


Figure 1. Maximum replacement level (expressed in %) of by-products and wastes for any aggregate ingredient. MSWI: municipal solid waste incineration, ISSA: incinerator sewage sludge ash, GGBFS: ground granulated blast furnace slag, EAFD: electric arc furnace dust.

Recycled aggregates, from mixed demolition wastes, are the most common alternative solution for green concretes. They are usually generated from crushed concrete or old composites to replace coarse aggregates with a larger diameter. Recycled concrete aggregate is made of a minimum of 95% crushed concrete. Various processes exist to produce quality recycled aggregates: plain and reinforced concrete detritus can be crushed using primary and secondary crushers. Resulting material usually contains pieces of metals, wood, or plastics that must be mechanically or manually removed before crushing. Common quality practices include crushing, screening, magnetic separation, and dry separation [32]. Recycled aggregates have been widely investigated in recent years and research has led to the conclusion that they have lower properties than corresponding natural aggregates [33,34]. The decrease in concrete quality firstly depends on the quality itself of the waste used. On the same mix proportion and workability, recycled aggregate concretes with 100% coarse aggregates substitution have an average compressive and tensile strength around 10–25% lower than ordinary concrete, with a 5% to 35% lower modulus of elasticity [35,36]. This lower performance is mainly associated with the cracks that generate during production: recycled coarse aggregates become more susceptible to permeation and absorption of fluids [37]. Literature results in terms of carbonation processes are contradictory: carbonation depth generally decreases with the percentage of recycled aggregate [38], but some investigations have shown opposite results [39,40]. The difference in the original aggregate influenced the result, but the different behaviour may be caused by test methodology, accelerated carbonation test in the first study, as the duration of exposure highly affects carbonation depth: the higher the exposure period, the higher the depth is.

Used in powder to replace sand, ceramic tile waste is also a possible substitute for coarse aggregates. Concrete mixtures with ceramic aggregates showed better performances than the control mixtures: with 20% of ceramic coarse aggregates, a similar compressive strength to high-performance conventional concretes can be achieved. Samples at 50% of replacement level at 180 days of curing have showed a low corrosion risk. A full replacement is achievable [41]. The properties of alternative aggregates from construction and demolition waste are listed in Table 1.

3.1.1. Physical Properties

Slump tests conducted over different samples integrating ceramic powder showed from 16 to 20 mm as the results for 15–30% fine aggregates substitution [42]. Dry density of specimens does not diverge from ordinary concrete, as for pore volume [43,44]. The samples studied by Lim et al. [30] with quarry dust integration showed a very high specific gravity and bulk density (3560 kg/m^3) due to the high iron content present in the electric arc furnace slag used as coarse aggregates.

The main consequence of the use of alternative coarse aggregate is the reduction in density caused by the lower bulk density of residues if compared to natural aggregates. Another common effect is the reduction in slump and initial workability, due to the higher water absorption, and the increase in porosity, that lead to a higher sensitivity to corrosion.

Incorporating ceramic coarse aggregates highly influence physical properties of concrete: the density decreases and, at the same time, absorption and voids volume increase with the replacement level [44]. Slump test results, around 40–50 mm, are in accordance with these data [42].

Recycled coarse aggregates showed a wide range of variation for slump depending on replacement level: data reported by Limbachiya et al. [39] underline an inverse proportion among slump effect and replacement share for conventional Portland cement, and a linear one for cement with FA integration. The incorporation of recycled aggregates led to an increase in thermal conductivity, which stood in a range of $0.7\text{--}1.1 \text{ W/(m K)}$ [34]. Nevertheless, composites are highly porous, nearly twice the porosity of normal concretes: this is a consequence of the higher porosity of the recycled aggregates, so the effect increases with the substitution. As a result, these concretes are more permeable to oxygen, double that of RC even if still relatively low. Higher water absorption rate and sensitivity to corrosion represent two additional dangerous side effects [45].

3.1.2. Mechanical Properties

Mechanical performance of the final specimens is strictly influenced by the resistance of aggregates. Construction and demolition waste is the class that showed the higher potential in terms of strength improvements: the compressive, flexural, and tensile resistance increased with the use of ceramic fine aggregates.

Results have shown that concrete produced with up to 30% of fine ceramic aggregates reach similar or improved mechanical properties than conventional concrete. According to some investigations [46,47] compressive strength of concretes with fine ceramic sand is higher than ordinary concretes, while other research got lower values [48]: the difference is due to the different quality of recycled ceramic wastes adopted, with a related different water absorption level. Compressive strength range between the reference and the studied specimens was higher during the first days: fine ceramic aggregate concretes achieved a greater early compressive strength as a result of their higher early absorption capacity as well as the higher specific surface of the fine aggregate. Flexural and tensile strengths were not highly affected by the substitution and so was the modulus of elasticity [44].

The quality of coarse aggregate directly influences the final performance of concrete, especially mechanical properties. Early stage improvements of mechanical resistance have been detected for construction and demolition wastes, but the long-term performance was lower than ordinary concretes due to the poor quality of artificial aggregates.

Investigations on coarse ceramic-based aggregates showed an increase in the compressive strength at an early stage, with an inverse proportion with replacement [48]. However, at 28 days, concretes presented lower values than RC, except for 20% coarse aggregate replacement. Early stage gain is mainly due to the high amount of free water within the mixture, while low final strength is linked to the poor quality of aggregate compared to conventional ones [44]. Recycled aggregates from old composites commonly follow this trend: research highlighted a decrease around 24–35% of mechanical properties [45]. Results achieved by Limbachiya et al. [32] instead, on recycled concretes, showed mechanical properties close to natural coarse aggregate concretes, with a slight deviation focused at high replacement levels.

3.1.3. Environmental Properties

A critical element for the integration of alternative aggregates is the heterogeneity of the material that determines highly variable properties of the final product [49]. The demolition phase impacts on the characterization and quality of the recycled aggregates: a selective process produces high quality, with more stable aggregates, as the result of a specific kind of waste, while a non-selective demolition results in a less homogeneous material, with a lower average performance [50].

The effect of construction and demolition waste aggregates on the porosity of the final product influence the durability of concrete by increasing the sorptivity, the absorption capacity and the chloride-ion penetration.

Durability properties of the recycled aggregate concretes are comparable to those of conventional concretes. The sorptivity and the water absorption of samples investigated by Gonzalez-Corominas et al. [44] have reached values close to RC. However, the resistance to chloride-ion penetration decreased as the recycled aggregate content increased, even if it still fit in low–very low corrosion risk level. Except for water permeability, even oxygen permeability and chloride diffusion performances have shown better results [48].

The use of ceramic coarse aggregates decreases density, and so final strength, due to the higher voids volume. Therefore, specimens with a higher rate of ceramic aggregates showed a greater sorptivity at 28 days. Absorption capacity and chloride-ion penetration are greater as well [44]. Even water absorption values surpassed the RC performance, but oxygen permeability and chloride diffusion confirmed the good behaviour of ceramic-based concrete [48].

Recycled aggregates, as other alternative materials, represent an environmentally friendly solution to prevent the amount of waste disposed in landfill [51]. Results of leaching tests carried out by Sani et al. [52] showed that a cumulated ion releases slightly higher than conventional concrete.

Release of pollutants become a relevant parameter for gypsum wastes, which produce a high release of sulphates [53].

Table 1. Physical, mechanical, and environmental performance of concrete products with alternative aggregates from construction and demolition wastes.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References		
<i>Fine aggregates</i>	Physical properties	Ceramic	Density	15–50%	2179–2184	kg/m ³				
			Slump test	5–30%	16–20 40–55	mm	ASTM Type I PC (0.2–0.5)	[42,44]		
			Volume of permeable pore space	5%	3.25	%		[44]		
	Mechanical properties	Ceramic	Granite dust	Density	50%	3560	kg/m ³	OPC (0.35)	[30]	
				Compressive strength (RC) ^{1,2}	50–100%	33.7–35.7 (33) 48 (40) 109.1 (102.6)	MPa	ASTM Type I PC 0.5–0.6	[42,44,48]	
				Flexural strength (RC) ³		6.55–8.31 (6.47)				
				Tensile strength (RC) ¹		5.14–5.25 (5.13)		ASTM Type I PC (0.2–0.5)	[44]	
		Modulus of elasticity (RC) ¹		47.6–49.9 (50.4)	GPa					
		Environmental properties	Ceramic	Granite quarry dust	Compressive strength (RC) ^{1,2}	50%	80 (80)	MPa	OPC (0.31–0.35)	[30]
					Absorption capacity ⁴	10–50%	1.3		ASTM Type I PC (0.285)	[44]
	Vacuum water absorption ⁴					17	%	OPC (0.5)	[48]	
	Water permeability				50–100%	5–6 × 10 ⁻¹⁷	m ²	ASTM Type I PC (0.285)	[42,48]	
	Oxygen permeability					8–9 × 10 ⁻¹⁷				
	Chloride-ion penetration ^{1,4}		1000 C	C						
	Chloride-ion diffusion ^{1,4}		23–26 × 10 ⁻¹²	m ² /s	OPC (0.5)	[48]				
<i>Coarse aggregates</i>	Physical properties	Recycled Aggregates	Sorptivity ¹	10–50%	0.015–0.016	mm/min ^{1/2}				
			Density		1800–1970	kg/m ³	PC CEM I 52.5 (0.5–0.55)	[33,44,51]		
			Slump ⁵	10–100%	20–70	mm	CEM IIA-LL 42.5 (0.5–0.74)	[39,54]		
			Porosity		6–23	%	CEMII/A-L42.5R (0.6)	[52,55]		
			Thermal conductivity		0.7–1.1 (0.65)	W/(m K)		[34,56]		
			Weighted sound reduction index	50%	64			ASTM type I OPC (0.29)		
			Weighted normalised impact sound pressure level		77	dB		[56]		

Table 1. Cont.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References
Coarse aggregates	Physical properties	Ceramic	Density	20–100%	2190–2430	kg/m ³	ASTM Type II PC (0.5–0.6)	[42,44]
			Bulk density	50%	1584			[42]
			Slump		40–50	mm		
			Volume of permeable pore space	20–100%	4.55–8.70	%		[44]
	Mechanical properties	Recycled Aggregates	Compressive strength (RC) ¹		20–27 (17)	MPa	OPC (0.5) PC	[31,33,38,44,53]
					24.4 (39.8)		CEM I 42.5 R/SR (0.5–0.6)	
			Flexural strength (RC) ¹	10–100%	4.3–4.5 (4.4)		CEM I 52.5 N/SR (0.45–0.65)	[31,38,53]
			Tensile strength (RC) ¹		2.6 (3.1)		PC CEM I 52.5 N (0.63)	[45]
		Modulus of elasticity (RC) ¹		19.6 (30.8)	GPa	PC CEM I 52.5 N/SR (0.45)	[31,38,44]	
		Ceramic	Compressive strength (RC) ¹		25.7–28.2 (26.9)	MPa	PC CEM I 42.5R (0.41–0.68)	[41,43,47]
					72–101 (102)			
			Flexural strength (RC) ¹	20–100%	4.7–6.9 (5–7)		ASTM Type II PC (0.5–0.6)	[44,57]
	Tensile strength (RC) ¹			4.2–4.6 (5.13)				
	Modulus of elasticity (RC) ¹		32.3–43.9 (50.4)			[44]		
	Environmental properties	Recycled Aggregates	pH		12		PC CEM II/A-LL 42.5 (0.74)	[54]
			Release of pollutants ^{6,7}	0–100%	0.18	mg Cr/kg	PC CEM I 52.5 N (0.5)	[58,59]
					0.007	mg Zn/kg		
					0.011	mg As/kg		
			Vacuum absorption capacity	20–100%	9.9–11.2	%	PC CEM I 52.5 N (0.63–0.65)	[45,55]
			Permeable coefficient		2–2.5	mm/s	ASTM type I OPC (0.29–0.45)	[34]
Cumulated ion releases ⁸			0–100%	4.5	mS/cm	PC CEMII/A-L42.5R (0.6)	[52]	
Soluble sulphate in water				2.4	%SO ₃ ⁻	PC CEM I 52.5 N (0.65)	[59]	
Soluble sulphate in acid		2.6						

Table 1. Cont.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References
			pH ⁹		8.5			
			Electrical conductivity of leachate		432	μS/cm		
			Release of pollutants ⁹	25%	0.065	mg B/(dm ² d)	CEM I 52.5 N/SR (0.45)	[60]
					0.038	mg Si/(dm ² d)		
					0.028	mg Cl/(dm ² d)		
		Ceramic	Absorption capacity	20–100%	1.88–3.97	%	ASTM Type II PC (0.5–0.6)	[42,44]
			Vacuum water absorption		18	%		
			Water permeability	50%	6×10^{-17}	m ²	ASTM type I OPC (0.55)	[48]
			Oxygen permeability		9×10^{-17}	m ²		
			Chloride-ion penetration ¹	20–100%	1100–1600	C	ASTM Type II PC (0.5–0.6)	[44]
			Chloride-ion diffusion ¹	50%	26×10^{-12}	m ² /s	ASTM type I OPC (0.55)	[48]
			Sorptivity ¹	20–100%	0.021–0.036	mm/min ^{1/2}	ASTM Type II PC (0.5–0.6)	[44]

RC: reference concrete; MSWI: municipal solid waste incineration; ISSA: incinerator sewage sludge ash; GGBFS: ground granulated blast furnace slag; EAFD: electric arc furnace dust; ASTM: American Society for Testing and Materials; OPC: ordinary portland cement; PC: Portland; CEM: cement. ¹ at 28 days; ² average; ³ 7 days; ⁴ average; ⁵ 30 MPa compressive strength targets at 28 days; ⁶ liquid to solid ratio 2; ⁷ EN 12457-3; ⁸ 100 h; ⁹ according to EN 14944-3.

3.2. Residues from Waste Treatment

MSWI ash has been tested as a proper solution for fine aggregates: “bulk chemical compositions of these wastes are similar to the compositions of various raw materials” so they can be incorporated as substitute of different concrete components [61,62]. MSWI Bottom Ash (BA) can replace the granular portion of concrete, both fine and coarse aggregates [63]. With a replacement level of 20–40% on sand weight, higher BA content has shown lower slump, a general increase in both initial and final setting time, and a reduction in compressive strength [64,65]. In waste management field, ISSA is a residue that finds different application in concrete industry: from cement component to concrete element in ground form. However, in fine particles, it can be adopted as a fine filler aggregate [66]. Due to the decrease in final strength of hardened composites, exploiting ISSA as a substitute of fine aggregates results a more advantageous solution than replacing cement. In particular, dried sludge can theoretically totally replace sand in concrete production, bringing a higher water absorption capacity and porosity, even if a maximum substitution of 20% has been investigated with positive results [67].

Gravel and coarse aggregates find in the upgraded MSWI BA another proper substitute. Artificial aggregates are produced by stabilization/solidification methods in a rotary plate granulator [68]. Even if a higher rate can be reached, a maximum replacement level around 20% in volume for structural concrete and up to 50% for plain concrete guarantee final mechanical and durability properties to be quite close to those of the ordinary concretes, at the same compressive strength. However, MSWI ash concrete have shown a higher shrinkage, creep, and chloride-diffusion coefficients [69]. Collivignarelli et al. [58] underlined the critical points for the environmental compatibility of aggregates based on MSWI ash: (i) the high amount of heavy metals, which affects durability; (ii) the high content of chloride, which enhances the steel corrosion. The problems concerning expansion and cracking are due to the development of gaseous hydrogen caused by the corrosion of metals in an alkaline environment [70]. Table 2 shows the properties of alternative aggregates from residues from waste treatment.

3.2.1. Physical Properties

Residues from waste treatment led to a reduction in workability due to the hygroscopic behaviour of ISSA particles and the increase in porosity, for MSWI ash, that reduce the final density. Addition of MSWI fine ash as fine aggregate influences physical properties of concrete: the workability gradually decreases while the porosity linearly increases with the substitution rate. Samples with different substitution rate studied by Kuo et al. [7] reported, with a porosity range of 24–27.5%, a slump test result of 270 mm. Fineness of ISSA particles underline its suitability as a substitute for fine aggregates. However, according to data [71], increasing the ISSA share in concrete significantly affect the workability: over a 15% of substitution rate zero slump is achievable. The cause can be found in a reduction in water/cement ratio and in the “hygroscopic nature” of ISSA particles due to the particles work in cement matrix as free water absorbers [72]. The use of sewage sludge (SS) as a substitute of fine aggregates has caused a reduction in density and an increase in capillary water absorption, thus partially compromising mechanical performance [72].

MSWI ashes can be properly implemented also as a substitute of coarse aggregates. BA, in fact, can replace the whole share of coarse aggregates in a mixture. The incorporation of MSWI ash aggregates reduces both the density and the slump [73]. According to the test carried out by Sorlini et al. [74] the washed ashes present physical qualities that comply with the production of concrete mixtures.

3.2.2. Mechanical Properties

Investigations on mechanical performance of MSWI ash-based concretes by Tang et al. [74] clearly showed the influence of recycled fine aggregates on compressive and flexural strength: a loss of 25% has been registered for compressive resistance at 30% of substitution. Flexural resistance was less influenced by the replacement, with a maximum loss of 10% at 20% of MSWI ash content [75].

The use of ISSA fine aggregates in concrete, instead, brought an enhanced cohesion in the matrix structure. As a result, an increased strength has been detected [71]. Compressive strength at 28 days of samples studied by Jamshidi et al. [72], with 20% of ISSA and a 0.45 water-to-cement ratio, reached 33 MPa.

The effect of MSWI ash replacement as a coarse aggregate on the mechanical properties of concrete is notably less than as a fine aggregate: average compressive strength decrease at 28 days is around 5% at 25% MSWI ash content. As “the coarse fraction of the ash has lower absorption properties than the fine fraction”, coarse aggregates have a lower interaction with the water movement and, along with higher concentration of sulphate and chloride salts, this may influence the hydration reaction and so the strength development [73]. Abbà et al. [70] noticed that the cement type of the mixture had a relevant role for the final performance, on an average base. The mixture with 42.5 R cement showed improvements both in compressive and tensile resistance, reducing the gap with ordinary concrete design.

3.2.3. Environmental Properties

Long-term performance of MSWI ash fine aggregates exceed the limit for concrete application: the leaching of Pb and Zn increased in MSWI ash concretes, with high concentration caused by the high pH environment.

Leaching test conducted on concrete samples made with MSWI ash fine aggregates has reported values lower than the untreated wastes for a series of pollutants, clearly confirming the effectiveness of the concrete stabilization. The leaching of Cu has been reduced, but on the other hand, leaching of Pb and Zn from the concretes containing wastes were in general higher than from the single waste. The concentrations of Cu and Pb exceeded the respective limit values. However, the lower levels of some elements from the mortar are due to chemical processes occurring during cement hydration. The high pH environment, instead, causes the high concentrations of Cu, Pb, and Zn [71].

Washing treatment is a common step in processing MSWI ashes to reduce the chloride content and prevent the reinforced concrete from corrosion risk. Leaching test results conducted by Keulen et al. [76] complied with standard reference: only salts release, mainly Cl and Br, increased at high replacement levels. Collivignarelli et al. [58] confirmed the environmental compatibility of MSWI ash aggregates in concrete by means of leaching tests, achieving a lower release than sand for chlorine, chromium, and bromine. The pollutants mobility and concentration have been highly influenced by the pH [77]. According to data reported by Sorlini et al. [65], different tests resulted in critical outcomes for different elements: 16 days leaching test for the release of anions, single stage in water for 24 h regarding the metals. Heavy metals critical values have been achieved in an acetic acid leaching test. However, the investigation confirmed that the overall leaching behaviour of the concrete with MSWI ash coarse aggregates was similar to natural concrete.

Table 2. Physical, mechanical, and environmental performance of concrete products with alternative aggregates from residues from waste treatment.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References
Fine aggregates	Physical properties	MSWI ash	Apparent density	40%	1.63	Mg/m ³	PC CEM I 52.5 R (0.67)	[78]
			Relative density		2.53	Mg/m ³		
			Slump test	25–90%	270	mm	ASTM C150 type I PC (1.6)	[7]
		Porosity	50% 25–90%	35.6 24–27.5	% %	ASTM C150 type I PC (1.6) PC CEM I 52.5 R (0.67)	[7,78]	
		Density ¹	5–20%	2100–2200	kg/m ³	OPC (0.45–0.55)	[72]	
		Slump test	5–15%	0–125	mm	ASTM C150 type I PC (0.5–0.6)	[71]	
		Void index	5–10%	9.5–9.8	%			
	Capillary water absorption coefficient ²	5–20%	0.55–0.9	kg/m ² h ^{1/2}	OPC (0.45–0.55)	[72]		
	Mechanical properties	MSWI ash	Compressive strength (RC) ³		65–75 (87)	MPa	PC CEM I 52.5 N (0.5–0.65)	[77,78]
				10–30%	20 (41)		ASTM C150 type I PC (0.5–0.6)	[73]
			Flexural strength (RC) ³		11–11.5 (12)	MPa	PC CEM I 52.5 N (0.5–0.65)	[75]
		ISSA	Compressive strength (RC) ^{1,3}	5–20%	24–33 (32)	MPa	OPC (0.45–0.55)	[72]
		Axial compressive strength (RC)	5–10%	25–28.8 (16.1)	MPa	ASTM C150 type I PC (0.5–0.6)	[71]	
	Flexural strength (RC) ^{1,3}	5–20%	3.5–4.5 (5)	MPa	OPC (0.45–0.55)	[72]		
	Environmental properties	MSWI ash	Release of pollutants ⁴			0.16–0.26	mg Cr/kg	PC CEM I 52.5 R (0.55–65)
				10–25%	0.21–0.36	mg Mo/kg		
					0.52–1.47	mg Pb/kg		
					0.29–0.31	mg Zn/kg		
ISSA		Water absorption	5–10%	4.19–4.38	%	ASTM C150 type I PC (0.5–0.6)	[71]	
Coarse aggregates	Physical properties	MSWI ash	Density	40–100%	2295–2331	kg/m ³	PC CEM II (0.36–0.5)	[76]
			Slump	100%	30–60	mm	ASTM C150 type I PC (0.5–0.6)	[73]
	Mechanical properties	MSWI ash	Compressive strength (RC) ²	60–90%	2–4.5 (5) 50–100 (55)	MPa	PC CEM32.5R-CEM42.5R (0.4–0.75)	[57,67,69,72,73]
			Flexural strength (RC) ³	10–100%	5.8–6.4 (6.7)		PC CEM II (0.36–0.5)	[74,76]
			Tensile strength (RC) ³	10–100%	5 (4.5)		ASTM C150 type I PC (0.5–0.6)	[57,69,75]

Table 2. Cont.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References
			Shrinkage ^{5–8}	25–100%	0.07–0.082	%	PC CEM I 52.5 R (0.4–0.6)	[73]
			Release of pollutants ⁹	60–90%	1–2	mg Zn/L		[68,74]
					5–11	mg Cr/L	PC CEM32.5R (0.4–0.75)	
					160	mg Cl/kg		
	Environmental properties	MSWI ash	Release of pollutants ¹⁰		0.2	mg Cu/kg		[64,75,76]
				40–100%	1.6	mg Br/kg	PC CEM I 52.5 R (0.67)	
			Release of pollutants ¹¹		0.012–0.014	mg Ba/L		[65,77]
					4.54–10.4	mg SO ₄ ²⁻ /L		
			pH		12.1–12.2		PC CEM II (0.36–0.5)	[76]

RC: reference concrete; MSWI: municipal solid waste incineration; ISSA: incinerator sewage sludge ash; GGBFS: ground granulated blast furnace slag; ASTM: American Society for Testing and Materials; OPC: ordinary portland cement; PC: Portland; CEM: cement. ¹ with 0.55 water-to-cement ratio; ² with 0.45 water-to-cement ratio; ³ at 28 days; ⁴ according to EN 12457-2; ⁵ average; ⁶ at 20 °C; ⁷ at 55% RH; ⁸ at 200 days; ⁹ 72h; ¹⁰ batch pH-static leaching according to EN 14997; ¹¹ according to UNI 10802.

3.3. Metallurgical Industry by-Products

Moving to metallurgical industry, concrete has shown to be a suitable material where waste foundry sands (WFS) can be adopted to partially replace natural fine aggregates [28]. This is a high-quality sand coming as a by-product of industrial metal castings [80]. The partial replacement through solidification/stabilization process, not exceeding 20% by weight, leads to a final product with performances close to RC [81]. Processed ground granulated blast furnace slag (GGBFS) becomes a granular product that can be dried and ground into a fine powder. In this shape, it is a natural substitute for fine aggregates: a 100% replacement of sand can be reached, but GGBFS incorporation hugely affects the final performance of composites. The compressive strength increased with an increasing GGBFS content [82]. Resistance to high temperature, surface abrasion, and durability properties of concrete are other characteristics affected by the substitution [83]. In road construction, there is a heavy metal industry waste suitable as a substitute: lead slag. Primary and secondary lead slag can be turned both in fine and coarse aggregates through a cement-based stabilization/solidification process [84]. It has shown a better grain size curve than sand itself, complying with the compressive strength requirements [85]. Alwaeli [86] has demonstrated that the incorporation of granulated lead–zinc slag in concrete works as a shield to the gamma radiation, so it would properly fit in laboratories construction where radiation are generally used. A full replacement of sand is theoretically achievable: results have shown that compressive strength increases with the content of lead slag.

Electric-arc furnace dust is a further typical metallurgical waste of the iron industry. Potentially, it can fully replace ordinary coarse aggregates [87]: benefits involve both mechanical and durability strength of final composite. Side effects of its incorporation, however, mainly concern the workability [88] and the dimensional stability performance [89]. The physical properties and chemical composition of electric-arc furnace dust widely varies according to the source, so a complete evaluation of its impact in concrete performance is difficult if not pre-processed to make it more stable [30]. The reduction in terms of workability is caused by a more uneven distribution of coarse aggregate size than RC, but both compressive, tensile, and shrinkage test attested the material reliability [90].

Blast furnace slag, instead, is a non-metallic by-product from iron industrial production, typically applied in asphalt concrete: it forms when iron is reduced into molten pig iron in blast furnaces. Depending on the final production process of the molten state iron, the slag can be classified into different types. Even if an increase in slag aggregates content generates a decrease in the mechanical properties of the final concrete, the loss of strength is very low with a complete replacement and nearly zero with a 50% of slag aggregates [91]. Table 3 lists the properties related to the alternative aggregates from metallurgical industry by-products.

3.3.1. Physical Properties

GGBFS presented the highest slump, around 180 mm, among waste treatments residues, which instead reduced the workability. The use of high-density lead slag increased the density of concrete, while the glass had the opposite effect because of its smaller specific density.

Clayey-type materials in WFS resulted in a decrease in fluidity and the slump test values of concrete when used to replace sand. The void index showed a quite constant trend until 10% of foundry sand content and it rapidly decreased beyond that threshold [80]. The density values were not highly affected by the replacement percentage, aligned to other by products used as fine aggregates [81]. The replacement of sand with GGBFS as fine aggregate improved the workability of concrete mixture: the slump test result moved from 150 mm of a conventional paste to 180 mm. This result may be caused by an increase in porosity: data reported by Valcuende et al. [92] show a proportional increase in porosity with the replacement level.

Concretes incorporating lead slag have shown a higher density compared to RC as a result of the high density of the slag itself [86]. At the same time, the addition of lead slag reduced the workability: samples analysed showed a lower slump than conventional concrete. The cause of this reduction is the use of finer materials “with more angular shapes” [93].

The substitution of coarse aggregates with electric arc furnace dust (EAFD) have led to a decrease in the initial workability [88]. This was a consequence of the higher water absorption: the investigations carried out by Arribas et al. [89] confirmed that the performance of concrete is caused by the porosity that increases with the share of EAFD, reaching 11.9%. Density of final composites, however, does not highly differ from RC [87]. Artificial aggregates made out of GGBFS showed an analogous behaviour causing a high water absorption and a lower workability in concretes [94]. The lower bulk density of GGBFS coarse aggregates influenced also the density of fresh and hardened concrete: the difference between test samples and reference was around 3% [91].

3.3.2. Mechanical Properties

Research showed different results in terms of compressive strength when WFS is used as fine aggregate: Khatib et al. [28] detected a “systematic decrease in compressive strength as the amount of WFS in concrete is increased”, while according to results presented by Siddique and Singh [80] “there was marginal increase in the compressive strength”. Different tests and investigations, instead, confirmed the low but positive impact of the substitution on the other mechanical properties like the flexural and tensile strength or the modulus of elasticity [80,95].

The replacement of fine aggregates with GGBFS has shown us how to enhance the overall mechanical performance of concrete: the compressive strength raised about 7.8% if compared to RC, and the effect of GGBFS increased up to 20% with a lower water-to-cement ratio. A similar trend has been detected by Teng et al. [96] in terms of both flexural strength, which raised of 7.5% with the addition of slag and modulus of elasticity. Even the effect of lead slag as fine aggregate on the mechanical properties of concretes varies in different research: according to Mosavinezhad et al. [93], results of the compressive strength of lead slag specimens at 28 days of curing “was 1% lower than those of the conventional concretes”. Investigations carried out by Alwaeli [86], instead, recommend an increase in the compressive strength between 20–40% with a target of 37.8 MPa. The flexural strength resulted slightly lower than ordinary concrete at 28 days, but the difference increased in the long term [93].

Concretes that integrate EAFD slag as coarse aggregate represent an exception, as they showed a higher compressive strength than RC due to the rough texture of aggregate surface, but an increase in waste addition led to lower values in terms of both tensile strength and modulus of elasticity [88]. On the opposite, Coppola et al. [87] results recommend a slight increase in flexural and splitting tensile strength, caused by the rough texture of EAFD aggregates and “the improvement of the transition zone at the interface of the aggregate and the cement matrix”. The higher water absorption caused another side effect as the shrinkage worsened by 30% with 25% of substitution.

The use of GGBFS, instead, led to a reduction in compressive strength up to 20.6% if compared to RC samples. The effect is caused by the lower compressive strength of slag aggregates than natural coarse aggregates, 100 MPa to 200 MPa, respectively [91]. The splitting tensile strength followed the same trend, with a percentage reduction in 17.4%, 8.2%, and 15.6% compared to RC, between 20% and 60% of replacement. The modulus of elasticity showed a similar behaviour, with an average decrease in 30% [97].

3.3.3. Environmental Properties

EAFD showed the best performance in terms of environmental compatibility as the results of leaching tests on the release of heavy metals complied with the threshold set by the legislation. The high concentration of chromium of GGBFS samples, instead, made them the less suitable alternative.

Tests conducted by Basar et al. [81] highlighted an increasing water absorption ratio with the addition of foundry sand: this trend align with the loss of compressive strength detected in some studies. The water absorption ratio of analysed specimens did not overcome 6% for 20% replacement ratio. As the detected heavy metal concentrations of the mixtures with different foundry sand content were compatible with standard limits, no adverse environmental effects have been associated with the

use of this kind of concrete. Compared to RC, samples with the integration of GGBFS have shown an improvement in resistance against chloride penetration as both chloride migration coefficient and chloride permeability reached lower values. In fact, the classification of resistance to chloride penetration moved from “moderate” to “high” and “extremely high”, while chloride permeability moved from “moderate” to “low”. The addition of lead slag at 28 days decreased the water absorption of concrete, that moved from 3.49% of standard specimen to 2.52%: although, long-term performance of lead slag concrete exceeded the ordinary value [93].

According to the sorptivity test made by Etxeberria et al. [88], 25% and 50% EAFD concretes were the most absorbent materials. These results attested the low water transmit by capillarity of these concretes. As a consequence, the leaching of heavy metals remains very low and conformed to legal standards [98]. GGBFS contains a high share of chromium that could cause environmental pollution issues during the usage and disposal life cycle steps. The results of leaching under standard TCLP test conditions showed a high concentration of chromium often exceeding the regulatory norms [99].

Table 3. Physical, mechanical, and environmental performance of concrete products with alternative aggregates from metallurgical industry by-products.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References	
<i>Fine aggregates</i>	Physical properties	Foundry sand	Density	10–40%	2361–2410	kg/m ³	OPC (0.28–0.35) Portland pozzolana FA-based cement (0.4–0.5)	[80,94,99]	
			Slump test	5–15%	60–150	mm	PC CEM I 42.5R (0.45–0.53) Portland pozzolana FA-based cement (0.4–0.5)	[79,94,99]	
			Initial setting time	10–40%	270–310	min	PC CEM I 42.5R (0.45–0.53)	[81]	
			Final setting time		4500–4800				
			Void index ¹	5–15%	5.6–5.9	%		[80]	
		GGBFS	Slump test ²	30%	180	mm	PC CEM II/B-M (S-L) 42.5R (0.55)	[92,96]	
			Porosity	10–60%	13.51–14.57	%			
		Lead slag	Density	25–100%	2210–2560	kg/m ³	Pozzolanic PC (0.4)	[86,93]	
			Slump test	30%	75	mm		[93]	
	Mechanical properties	Foundry sand	Compressive strength (RC) ³	30–100%	19–33 (40) 29–30 (28)	MPa	PC CEM I 42.5R (0.45–0.53) Portland pozzolana FA-based cement	[27,79,94,100]	
			Flexural strength (RC) ³	10–30%	3.4–3.7 (3.3)			[80,95]	
			Tensile strength (RC) ³	5–20%	2.8–3 (2.7)		43 grade OPC (0.5)	[80,95]	
			Modulus of elasticity (RC) ³	10–30%	27–28 (25) 30.5–31.5 (30)	GPa	[80,95]		
			GGBFS	Compressive strength (RC) ³	10–50% 30%	42–52 (52) 82.5 (76.5)	MPa	43 grade OPC (0.4–0.44)	[83,92,96]
		Flexural strength (RC) ³		30%	7.2 (6.7)				
Modulus of elasticity (RC) ³				3.64 (3.07)	GPa	OPC (0.28–0.35)	[96]		
Lead slag		Compressive strength (RC) ³	25–100% 30%	40–50 (37.8) 18 (18)	MPa	Limestone PCCEM II/A-LL 42.5R (0.54) ASTM Type I PC (0.29–0.58)	[84,85,92]		

Table 3. Cont.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References		
Coarse aggregates	Environmental properties	Foundry sand	Flexural strength (RC) ³	30%	0.9 (1)		43 grade OPC (0.4–0.44)	[93]		
			Release of pollutants ⁴	10–40%	0.013–0.022	mg Zn/L	PC CEM I 42.5R (0.45–0.53)	[81]		
					0.029–0.039	mg Cr/L				
			Water absorption ³	5–15%	2.4–2.5	%		[80,81]		
			Chloride Permeability ³	5–20%	1060–1250	C	Portland pozzolana FA-based cement (0.4–0.5)	[100,101]		
			GGBFS	Chloride migration coefficient ³	30%	7.92×10^{-12}	m ² /s	OPC (0.28–0.35)	[96]	
		Chloride permeability ³		2097		C				
		Lead slag	Water absorption		2.52	%	43 grade OPC (0.4–0.44)	[93]		
		Coarse aggregates	Physical properties	EAFD	Density	10–25%	2435–2500	kg/m ³	Limestone Portland Cement CE II/A-LL 42.5R (0.54)	[87]
					Slump	100%	55–90	mm	PC CEM I 52.5R (0.55–0.69) ASTM C150 Type I, PC (0.59/0.69) PC CEM II/A-LL 32.5R (0.43) 43 grade OPC (0.32)	[86–88,101]
Porosity							10.1–11.9	%	ASTM C150 Type I PC (0.59/0.69)	[89]
GGBFS	Density			50–100%	2309–2341	kg/m ³	PC CEM II/A-LL 32.5R (0.43)	[91]		
	Slump				150–175	mm	PC CEM II/B-M (S-L) 42.5R (0.55)	[90,93,102]		

Table 3. Cont.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References	
	Mechanical properties	EAFD	Compressive strength (RC) ³	25–100%	20.3–24.1 (22)	MPa	PC CEM I 52.5R (0.55–0.69)	[87–90,102]	
					55 (40)		ASTM C150 Type I PC (0.59/0.69)		
			Flexural strength (RC) ³	8–9 (9)	PC CEM II/A-LL 32.5R (0.43)		[90]		
					43 grade OPC (0.32)				
			Splitting tensile strength (RC) ³	1.8–2.5 (2.4)	PC CEM II/A-LL 32.5R (0.43)		[87,88]		
		GGBFS	Shrinkage ³	10–25%	0.7–0.5	mm/m	Limestone PC CEM II/A-LL 42.5R (0.54)	[87,90]	
							Modulus of elasticity (RC) ³		25–100%
			Compressive strength (RC) ³	20–100%	43.1–47.9 (55.8)			MPa	
					64.2–69.7 (60.9)				
			Splitting tensile strength (RC) ³	50–100%	3.77–3.96 (4.67)		GPa	PC CEM II/B-M (S-L) 42.5R (0.5–0.6)	[91,97]
Modulus of elasticity (RC) ³	27.4–28.8 (34.6)	PC CEM II/A-LL 32.5R (0.4–0.5)							
Environmental properties	EAFD	Release of pollutants	100%	5.5	mg Si/L	Limestone PC, CEMII/A-L 42.5R (0.45–0.54)	[98]		
		Sorptivity	25–100%	0.04–0.08	mm/min ^{1/2}	[88]			
	GGBFS	Release of pollutants ⁴	20–100%	28–35	mg Cr /L	OPC (0.5) Blended Portland Slag Cement (0.5)	[99]		
		pH	10.95–11.12	mg Cr /L	Portland Pozollana				

RC: reference concrete; MSWI: municipal solid waste incineration; ISSA: incinerator sewage sludge ash; GGBFS: ground granulated blast furnace slag; ASTM: American Society for Testing and Materials; OPC: ordinary portland cement; PC: Portland; CEM: cement. ¹ at 28 days; ² with 0.6% of superplasticizer; ³ at 28 days; ⁴ according to EN 12457-4 with a pH of 5.5, by Toxicity Characteristic Leaching Procedure test.

3.4. Other By-Products

Coming from a completely different sector, mixed sheet glass is another kind of waste mainly disposed to landfill that can be recycled in concrete manufacturing. The substitution of natural sand and fine aggregates with sheet glass powder represents both an economical way to manage waste glass and a natural resources conservation strategy. With a replacement percentage around 10–20%, the concrete performances are perfectly aligned with those containing natural sand aggregates [104]. In fact, the chemical composition and the pozzolanic properties of glass resemble those of sand [105]. Particle size mainly affects the concrete performance in bearing capacity and cohesion. A low particle size guarantees the pozzolanic reaction between the waste glass and the cement producing a higher resistance [105,106]. The decrease in the flexural strength of the final product in case of excessive waste glass addition is caused by a lower adhesion [107] due to the glass particle surface [108,109]. Recycled glass from bottles is another source for alternative fine aggregates. It decreases the water–cement ratio and the unit weight of concrete [110].

The possibility of using broken glass as a substitute for concrete coarse aggregate represents an alternative solution. Experiment have shown that recycled glass has a limit of 10% of replacement level in terms of weight in concrete mixtures: 5% weight incorporation presents a proper compressive strength result [111]. Properties related to alternative aggregates from other by-products are listed in Table 4.

Moving to other materials, an alternative substitute of fine aggregate in concrete is crumb rubber. Made from reprocessing of automobile tyres, crumb rubber can range from 0% to 100% in replacement of crushed sand in concrete mixtures. However, a 25% level guaranteed an acceptable compressive strength [112]. Concrete mix design based on pelletized cut rubber tyre particles have been tasted as an alternative mixture. The benefits of waste rubber incorporation account for more economical and cost-efficient final composites. Performance of such a concrete is not aligned with structural concrete requirements though, mainly because of the decrease in strength due to the weak bond between the rubber particles and the cement [113]. As in clinker production, Polyethylene terephthalate (PET) can also replace fine aggregates in a low range, around 5–6%. The use of recycled PET bottle fibres increases compression and tensile strength of concrete composites and reduces the quantity of sand needed [114].

Even polyethylene terephthalate is a suitable alternative aggregate: plastic fibre aggregates are obtained by shredding, melting, and crushing the collected waste PET bottles. By increasing the PET replacement rate, a lower compressive strengths is observed, but proper performances are shown for a 20% ratio, with an higher workability than ordinary concrete [115].

3.4.1. Physical Properties

The smaller relative density of glass sand, if compared to natural fine aggregates, led to a lower density of the final composites. The fresh density was not affected by glass colour under 75% of replacement: at full substitution brown, green, clear, and mixed coloured glass sand concrete density reached 97%, 96%, 95%, and 97% of that of RC, respectively. The paste workability increased together with the share of glass powder added, but it decreased with the curing days. This effect is due to the alkali silica reaction.

Tests results have shown a linear relation between glass addition and unit weight, with a decrease in density for higher shares of glass. The decline has been attributed to the lower specific gravity of waste glass if compared to natural coarse aggregates [116]. Samples also showed a reduction in workability as a result of the slump tests.

3.4.2. Mechanical Properties

Glass powder registered a loss around 10–20% of both compressive and flexural resistance due to the particle size that can cause the cracking of the aggregate. At lower replacement levels,

the use of glass sand instead of natural sand does not highly affect the mechanical performance of concrete: compressive, flexural, and tensile strength are close to RC under 10–15% of substitution. Nevertheless, different research [105,117,118] has shown that the alkali–silica reaction is responsible for cracking of aggregates during the production phase. The particle size has been proven to influence this process, as it increases with increasing the particle sizes of the waste glass aggregate. Therefore, compressive strength results lower, around 51% than RC, when increasing the percentage of glass powder up to 60%. A similar trend has been detected when investigating on the flexural strength: the reduction with an increasing percentage of the waste glass aggregate depends on the decrease in adhesive strength of glass particle surface [104,105]. Tensile strength, instead, showed the opposite behaviour increasing with the amount of glass used as fine aggregate [109].

Glass-based coarse aggregates cause a reduction in the overall mechanical performance of concrete: the compressive strength decreased around 26%, due to the “smooth surface texture of these aggregates and poor bonding properties of the matrix”. Sekar et al. [119] presented similar results in terms of tensile and flexural strength. Research has shown contradictory results concerning the modulus of elasticity: while some studies reported an increase in the modulus along with the replacement level [120,121], other investigations recommended a decrease around 40% [116]. A higher value of the modulus of elasticity can be explained by the finely divided waste glass that positively affects the bond properties.

3.4.3. Environmental Properties

Glass particle finesses and low porosity of specimens showed a positive effect increasing the resistance to chloride ion penetration. Concrete mixture integrating glass powder showed “no segregation or bleeding during mixing and casting” [105]. In terms of chloride permeability, all the mixtures with a range share of glass powder between 0–50% presented high values: the highest, 6764 Coulombs, in the case of natural sand. Glass colour affected this property as the charges passed with a 50% replacement level for brown, green, clear, and mixed glass sand were 93%, 69%, 71%, and 64%, respectively. The lower porosity and the finer size of glass particles integrated in concrete have positively affected the resistance to chloride ion penetration. Regarding sulphate attack, the different mixtures registered comparable weight loss [109].

The use of glass aggregate in concrete has led to a higher concentration of Pb as underlined by Synthetic Precipitation Leaching Procedure tests carried out by Romero et al. [122]. The performance must be more deeply investigated in order to evaluate the properties referred to a monolithic specimen, which are most influenced by diffusion.

Table 4. Physical, mechanical, and environmental performance of concrete products with alternative aggregates from other by-products.

Aggregate	Property Class	Substitute By-Product	Property	Replacement Level	Value	Unit of Measurement	Cement Type (Water-to-Cement Ratio)	References
<i>Fine aggregates</i>	Physical properties	Glass	Relative density	10–50%	3.14–3.27		PC CEM II/B-M (S-L) 42.5R (0.5–0.6)	[104]
			Fresh density	25–100%	2220–2110	kg/m ³	ASTM Type I PC (0.47–0.485)	[109]
			Porosity	10–50%	33–35	%	PC CEM II/B-M (S-L) 42.5R (0.5–0.6)	[104]
	Mechanical properties		Thermal conductivity	15–45%	0.1–0.18	W/(m K)	OPC (0.4–0.5)	[123]
			Compressive strength (RC) ¹	10–50%	35–40 (40)	MPa	OPC (0.5–0.6)	[103,104,108]
			Flexural strength (RC) ¹	25–100%	34–54 (52)			
			Tensile strength (RC) ¹	10–50%	5–7 (7)			
	Modulus of elasticity (RC) ²		25–100%	23–29 (30)	GPa			
	Environmental properties		Chloride permeability ³	25–100%	2500–6200	C	ASTM Type I PC (0.47–0.485)	[109]
			Sulphate attack (weight loss %)		4.5–5	%		
<i>Coarse aggregates</i>	Physical properties	Glass	Density	5–40%	2330–2340	kg/m ³	Compose PKC/B 32.5R (0.54)	[116]
			Slump		10–89	mm	43 grade OPC (0.5–0.6)	[116,124]
	Mechanical properties		Compressive strength (RC) ³	5–40%	13.2–20.6 (19.3)	MPa	43 grade OPC (0.5–0.6)	[116,119]
			Flexural strength (RC) ³	40%	13.94 (17.13)			
			Splitting tensile strength (RC) ³	40%	2.94 (3.24)			
			Modulus of elasticity (RC) ³	5–40%	50–22 (59.9)			
	Environmental properties		Release of pollutants ⁴	5–40%	0.016–0.132	mg Pb /L	OPC (0.4–0.6)	[122]
			Release of pollutants	10–30%	0.5–100 ⁵	mg Pb /L		

RC: reference concrete; MSWI: municipal solid waste incineration; ISSA: incinerator sewage sludge ash; GGBFS: ground granulated blast furnace slag; EAFD: electric arc furnace dust; ASTM: American Society for Testing and Materials; OPC: ordinary portland cement; PC: Portland; CEM: cement. ¹ at 28 days; ² static; ³ at 28 days; ⁴ by Synthetic Precipitation Leaching Procedure test; ⁵ the release is strongly dependent on the pH value.

4. Discussion

The increasing urbanization is leading to a massive production of concrete, thus of aggregates, with a dangerous effect on non-renewable natural resources, such as river sand and limestone, due to an increasing extraction rate [126]. Even if the building industry is the second largest in generating waste, with construction sector responsible for around 30% of the waste produced, recycled aggregates only represent the 3% of the total demand [127]. Recent research has focused on possible applications of recycled aggregates to suitably replace natural ones in creating sustainable concrete, checking mechanical properties, durability, environmental impact, and cost [128].

In this framework, determining the properties of final products that integrate alternative aggregates is an essential step to define their suitability in civil applications. Table 5 summarizes the results of the main alternative aggregates among those investigated, resuming some of the most relevant properties for each element analysed. Even if determining the best alternative aggregate is not possible as the mixtures investigated present different proportions and binders, general trends can be outlined. Regarding physical properties, all the alternative aggregates show density values close to reference ones, with the exception of recycled coarse aggregate and MSWI ash-based fine aggregates, which were characterized by low density values, mainly due to the quality of the original waste. Incorporation of waste and discards generally led to a decrease in the workability and density, as artificial recycled products usually showed lower density and pozzolanic activity than natural aggregates. Concerning the workability, GGBFS aggregates had a positive impact on hardened samples, with 180 mm of slump, due to the increased porosity. Regarding the mechanical resistance, ceramic showed the better overall performance, increasing the compressive, flexural, and tensile strength, compared to the target of the reference concrete. Other alternatives reduce the mechanical performance, with MSWI ash, ISSA, and glass recording the worst behaviour. The substitution of coarse aggregate, in fact, usually led to a decrease in the overall resistance, due to the poorer properties of artificial aggregates compared to natural ones, except for EAFD. Fine aggregates replacement, instead, enhanced the performance around 10–20%, with EAFD and ceramic waste showing the best improvement. Looking at the environmental compatibility of alternative aggregates, generally the resistance to chloride ion penetration improves, while pollutant release depends on the kind of waste used: it is related to metallurgical by-products, that mainly affect Cr, Pb, and Si release. Construction and demolition wastes, as products already used in buildings, usually complied with the legislation thresholds, while residues from waste treatment and metallurgical industry as a substitute for fine aggregates exceeded the maximum values allowed for construction application, both in the case of lead slag and MSWI ash. Globally, ceramic represent the alternative aggregate with the highest potential, both for fine and coarse aggregates, while MSWI ash-based aggregates determine a relevant loss in both the physical and mechanical performance of concrete.

The present work has focused on the properties of the final products that integrate alternative aggregates coming from four main waste streams not considering the properties of alternative materials themselves. International legislation and national regulations, nevertheless, define limits and set a minimum performance that materials must answer to before they could be used in concrete production [65]. The properties of aggregates are set by the UNI EN 12620, which defines chemical, physical, and geometric properties. The range in the performance value mainly depends on two influencing factors: the replacement level and the mixture components or proportion. The replacement level influences the performance linearly with the quality of alternative product: the integration of recycled aggregates, for example, that show lower properties and quality than conventional ones impacts on final product according to the substitution rate. As the data collected state, the substitution rates are lower for fine aggregates if compared to coarse ones: this underlines the higher impact that fine aggregates substitution has on final product compared to coarse ones, as they influence cohesion and resistance of the mixture. As ordinary concrete, the range of values is linked to the water-to-binder ratio used in each specific research activity and the kind of cement, mainly Portland, whose composition interacts differently with alternative aggregates.

Table 5. Physical, mechanical, and environmental performance of concrete products with alternative aggregates.

Waste Stream	Substitute By-Product	Property Class	Property	Value		Unit of Measurement
				Fine Aggregate [Replacement Level]	Coarse Aggregate [Replacement Level]	
<i>Construction and demolition wastes</i>	Ceramic	Physical properties	Density	2179–2184 [15–50%]	2190–2430 [20–100%]	kg/m ³
			Mechanical properties	Compressive strength (RC)	33.7–35.7 (33) [50–100%]	25.7–28.2 (26.9) [20–100%]
		Flexural strength (RC)		6.55–8.31 (6.47) [50–100%]	4.7–6.9 (5–7) [20–100%]	
		Tensile strength (RC)		5.14–5.25 (5.13) [50–100%]	4.2–4.6 (5.13) [20–100%]	
		Environmental properties		Absorption capacity	1.3 [50–100%]	1.88–3.97 [20–100%]
			Water permeability	$5-6 \times 10^{-17}$ [50–100%]	6×10^{-17} [50%]	m ²
	Chloride-ion penetration	1000 [50–100%]	1100–1600 [20–100%]	C		
	Recycled Aggregates	Physical properties	Density	-	1800–1970 [10–100%]	kg/m ³
			Mechanical properties	Compressive strength (RC)	-	20–27 (17) [10–100%]
		Flexural strength (RC)		-	4.3–4.5 (4.4) [10–100%]	
		Tensile strength (RC)		-	2.6 (3.1) [10–100%]	
		Environmental properties		Release of pollutants ⁶	-	0.18
-			0.007		mg Zn/kg	
-	0.011		mg As/kg			

Table 5. Cont.

Waste Stream	Substitute By-Product	Property Class	Property	Value		Unit of Measurement
				Fine Aggregate [Replacement Level]	Coarse Aggregate [Replacement Level]	
<i>Residues from waste treatment</i>	MSWIAsh	Physical properties	Density	1630 [40%]	2295–2331	kg/m ³
		Mechanical properties	Compressive strength (RC)	65–75 (87) [10–30%]	2–4.5 (5) [60–90%]	MPa
			Flexural strength (RC)	11–11.5 (12) [10–30%]	5.8–6.4 (6.7) [10–100%]	
	Environmental properties	Release of pollutants ⁹	0.16–0.26	5–11 [60–90%]	mg Cr/L	
	ISSA	Physical properties	Density	2100–2200 [5–20%]	-	kg/m ³
		Mechanical properties	Compressive strength (RC)	24–33 (32) [5–20%]	-	MPa
			Flexural strength (RC)	3.5–4.5 (5) [5–20%]	-	
		Environmental properties	Water absorption	4.19–4.38 [5–10%]	-	%
	<i>Metallurgical industry by-products</i>	GGBFS	Physical properties	Density	-	2309–2341
Mechanical properties			Compressive strength	42–52 (52) [10–50%]	20.3–24.1 (22) [25–100%]	MPa
			Flexural strength (RC)	7.2 (6.7) [30%]	-	
			Splitting tensile strength (RC)	-	3.77–3.96 (4.67) [50–100%]	
Environmental properties		Chloride permeability	2097	-	C	
		Release of pollutants	-	28–35	mg Cr /L	
Foundry sand		Physical properties	Density	2361–2410 [10–40%]	-	kg/m ³
		Mechanical properties	Compressive strength	19–33 (40) [30–100%]	-	MPa
			Flexural strength (RC)	3.4–3.7 (3.3) [10–30%]	-	

Table 5. Cont.

Waste Stream	Substitute By-Product	Property Class	Property	Value		Unit of Measurement		
				Fine Aggregate [Replacement Level]	Coarse Aggregate [Replacement Level]			
Other by-products	EAFD		Tensile strength (RC)	2.8–3 (2.7) [5–20%]	-			
		Environmental properties	Release of pollutants	0.029–0.039	-	mg Cr/L		
		Physical properties	Density	-	2435–2500 [10–25%]	kg/m ³		
		Mechanical properties	Compressive strength	-	55 (40) [25–100%]	MPa		
			Flexural strength (RC)	-	8–9 (9) [25–100%]			
			Tensile strength (RC)	-	1.8–2.5 (2.4) [25–100%]			
		Environmental properties	Release of pollutants	-	5.5 [100%]	mg Si/L		
		Other by-products	Glass	Physical properties	Density	2220–2110 [25–100%]	2330–2340 [5–40%]	kg/m ³
				Mechanical properties	Compressive strength	34–54 (52) [10–50%]	13.2–20.6 (19.3) [5–40%]	MPa
					Flexural strength (RC)	5–7 (7) [10–50%]	13.94 (17.13) [40%]	
Tensile strength (RC)	6–10 (7) [10–50%]				2.94 (3.24) [40%]			
Environmental properties	Chloride permeability			2500–6200 [25–100%]	-	C		
	Release of pollutants			-	0.016–0.132 [5–40%]	mg Pb /L		

Looking to impact, research highlights the potential of reducing environmental footprint, mainly regarding the landfill use: a reduction between 6% and 8% and between 19% and 23% when 30% and 100% of fine aggregates are replaced [129].

The advantages of recycled aggregates rather than common ones in concrete result mainly in the terms of land use, when related to the exploitation of the quarry [130]. Various factors affect the magnitude of possible environmental impact of alternative materials, moving from the recycling process, and related embodied energies, to transportation: a linear correlation links the effect of alternative aggregates integration and the variation in transportation distances compared with natural aggregates. The unit contribution of aggregates to the total CO₂ emissions is low, but it becomes relevant considering the amount of aggregate in the total concrete volume.

Turk et al. carried out an LCA analysis on samples made with (i) foundry sand, (ii) steel slag, and (iii) recycled aggregates from reinforced concrete waste: major common benefit was related to avoidance of the need to dispose of the waste materials, while extra credit came from the recovery of scrap iron from the steel reinforcement, in case of recycled aggregates, and from the recovery of metals, when dealing with steel slag. Research confirmed that the possible long delivery distance represents the main disadvantage. Results showed that fly ash and foundry sand, especially combined with recycled aggregates: a reduction in environmental impact around 75%, 85%, and 95% has been detected for fly ash, foundry sands, and EAF slag, respectively. The last case showed a neglectable improvement of CO₂ emissions, but a very significant impact with regard to Eutrophication [131]. Recycled aggregates proved to be less efficient in reducing greenhouse gas emissions [132].

5. Conclusions

To reduce concrete-related CO₂ emissions, the integration of wastes and by-products as components in concrete production is a promising strategy: the magnitude of their effect, however, is strictly linked to the properties of the final product, which must comply with the requirements for common applications. The most relevant and investigated characteristics are mechanical properties and environmental compatibilities, particularly heavy metal release-related ones: a deeper investigation is needed on physical side as analysis mainly focuses on density and workability, since they have a direct relapse on the manufacturing process, but little information is available for acoustical and thermal properties. A proper thermal characterization of concretes with alternative aggregates would be significant even for the evaluation of fire resistance performance.

In conclusion, the aggregate substitution proved to have a high impact on properties: GGBFS showed the highest potential, with positive effects on workability as a fine aggregate substitute, along with EAFD and ceramic powder, which improved the durability and mechanical properties of concrete. Excluding quarry dust and ISSA for fine aggregates, and glass for coarse ones, generally aggregates can easily reach a complete replacement with other alternative materials, but high substitution rates commonly generate relevant side effects.

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Abbreviations

AITEC	Italian Technical and Economic Cement Association
ANCE	Italian Association of Building Contractors
ASTM	American Society for Testing and Materials
ATECAP	Italian Technical and Economic Association of Precast Concrete
BA	bottom ash
BIBM	European Federation for precast concrete

CEM	cement
EAFD	electric arc furnace dust
ECRA	European Cement Research Academy
ERMCO	European Ready Mixed Concrete Organization
FA	fly ash
GCCA	Global Cement and Concrete Association
GGBFS	ground granulated blast furnace slag
GHG	greenhouse gas
IEA	International Energy Agency
ISSA	incinerator sewage sludge ash
MSWI	municipal solid waste incineration
OPC	ordinary Portland cement
PC	Portland cement
PET	polyethylene terephthalate
PVC	polyvinyl chloride
RC	reference concrete
SPLP	synthetic precipitation leaching procedure
SS	sewage sludge
TCLP	toxicity characteristic leaching procedure
WFS	waste foundry sand

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