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Review

Resource utilization of municipal solid waste incineration residues in cement-based materials: A review

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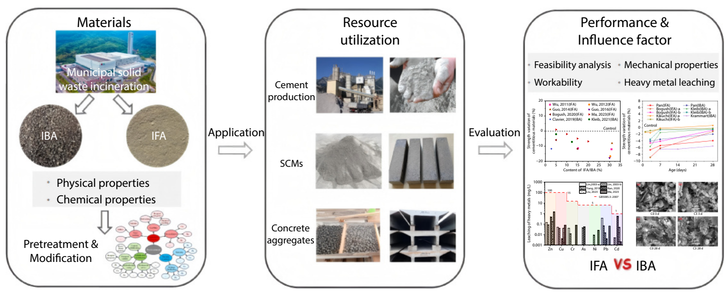
Abstract: The growing volume of municipal solid waste incineration residues (MSWIR) has made their effective management an urgent environmental concern. Due to MSWIR's favorable mineral components and cementitious properties, its potential application in cement concrete has been garnering growing attention. This paper reviews the chemical composition of MSWIR from different regions and the properties of cement-based materials containing MSWIR. It discusses the advantages and disadvantages of various resource utilization pathways for MSWIR, investigates the challenges faced in using MSWIR as a mineral resource for producing cement-based materials, and analyzes the possible causes. Additionally, it provides feasible solutions to address these challenges. This review indicates that the physicochemical properties of MSWIR exhibit significant regional characteristics. Although the incorporation of MSWIR often weakens the performance of cement-based materials, it demonstrates considerable potential as a raw material for cement, a supplementary cementitious material, and a substitute for concrete aggregates when its threshold is properly controlled. Both incineration fly ash (IFA) and incineration bottom ash (IBA) possess distinct advantages and disadvantages in their resource utilization pathways. It is worth noting that while the short-term performance of MSWIR products meets regulatory requirements, their long-term performance requires further investigation.



Keywords: municipal solid waste incineration residues, incineration fly ash, incineration bottom ash, resource utilization, cement-based materials, performance, mechanism

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1. Introduction

With the acceleration of urbanization and the improvement of living standards, the volume of municipal solid waste (MSW) is rapidly increasing. The World Bank predicts that by 2050, the global annual waste generation will reach 3.4 bil-

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lion tons, representing an approximate 69.15% increase from 2.01 billion tons in 2018[1]. According to official domestic data from China[2], in 2023, the volume of MSW exceeded 254 million tons, an increase of approximately 65.01% compared to 154 million tons in 2013. This large-scale waste generation poses a serious threat to human health and environmental safety, making the management of MSW an urgent task for contemporary society[3].

Currently, landfill and incineration are the main methods of waste disposal[4]. Before 2019, MSW was primarily disposed of through landfilling, a technologically mature and cost-effective method, but it has significant drawbacks such as occupying large areas of land and causing groundwater pollution, soil contamination, and odor emissions[5]. With the development of incineration technology, incineration has gradually become the main method of MSW disposal due to its significant advantages in volume reduction, weight reduction, and environmental protection. Fig. 1 shows the statistics on the status of harmless waste incineration treatment in China from 2013 to 2023. The figure indicates a continuous growth trend in waste incineration treatment volume in the 11 years. Since 2019, the proportion of incineration treatment has exceeded 50%, making it the primary method for harmless waste disposal. Waste incineration can effectively reduce the mass and volume of waste by approximately 70% and 90%, respectively, and can also achieve resource recovery through heat and power generation. This method offers excellent resource utilization, volume reduction, and harmless treatment effects, making it widely adopted[1,6,7]. However, with the increase in the amount of MSW incinerated, the issue of managing the resulting municipal solid waste incineration residues (MSWIR) has become a new challenge.

The mass of MSWIR generated from waste incineration is substantial, with China's MSWIR amounting to nearly 62.8 million tons in 2023. Most MSWIR is disposed of through landfilling, which occupies large land areas, highlighting the urgent need to explore more effective recycling pathways[8]. A smaller portion contains significant amounts of heavy metals and toxic substances, requiring treatment before it can be utilized as a resource. Thus, the proper disposal of MSWIR holds immense potential, not only helping to reduce resource depletion and save land but also bringing environmental protection benefits and creating considerable economic value.

Fig. 2 illustrates the keyword co-occurrence network for research related to MSWIR. The figure shows that keywords such as “fly ash”, “heavy metals”, “bottom ash”, and “combustion” form core clusters, reflecting research hotspots that encompass pollution control, resource utilization, and combustion emission management. From a temporal perspective, early studies focused more on the physical and chemical properties of fly ash and bottom ash, as well as pollutant indicators. Subsequently, the focus shifted toward applications in heavy metal adsorption, pollutant control, and green treatment technologies.

In recent years, the application of MSWIR in construction materials and its performance enhancement have gradually emerged as prominent research topics. Gress et al.[9] conducted experiments using MSWIR as a substitute aggregate in asphalt concrete. The experimental results indicated that MSWIR could be effectively encapsulated by asphalt, reducing salt leaching rates and facilitating the resource utilization of bottom ash. Xue et al.[10] utilized MSWIR as an aggregate in stone matrix asphalt mixtures, which revealed that the performance of the mixtures met the required standards and that the asphalt demonstrated the ability to inhibit the leaching of heavy metals. Wu et al.[11] successfully replaced 30% of the cement raw materials with MSWIR, finding that the performance of the cement clinker met the required standards and the leaching of heavy metals complied with the regulations. Currently, MSWIR can be primarily used in the field of cement-based materials as a raw material for cement, a supplementary cementitious material, and a substitute for concrete aggregates. By employing different treatment technologies according to the specific physical and chemical properties of

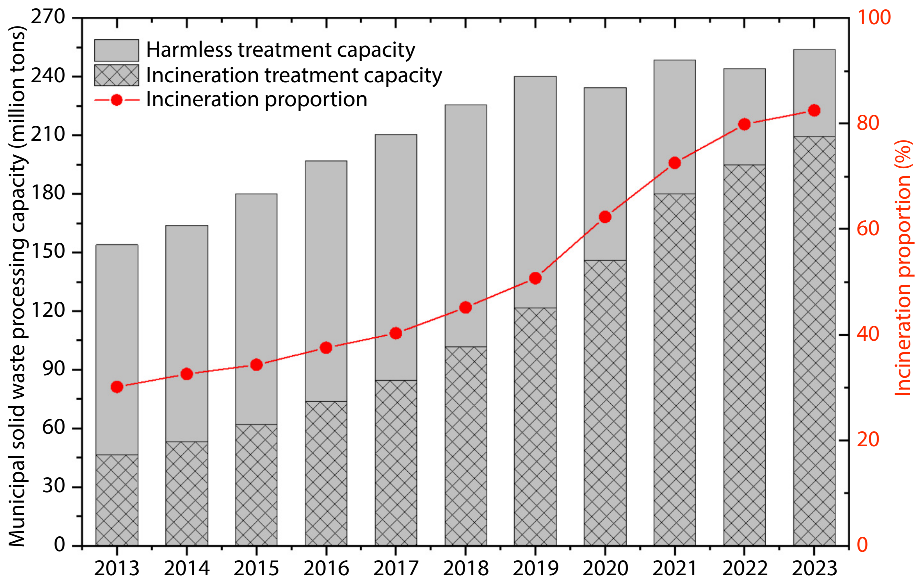

Fig. 1. Status of waste incineration in China from 2013 to 2023.

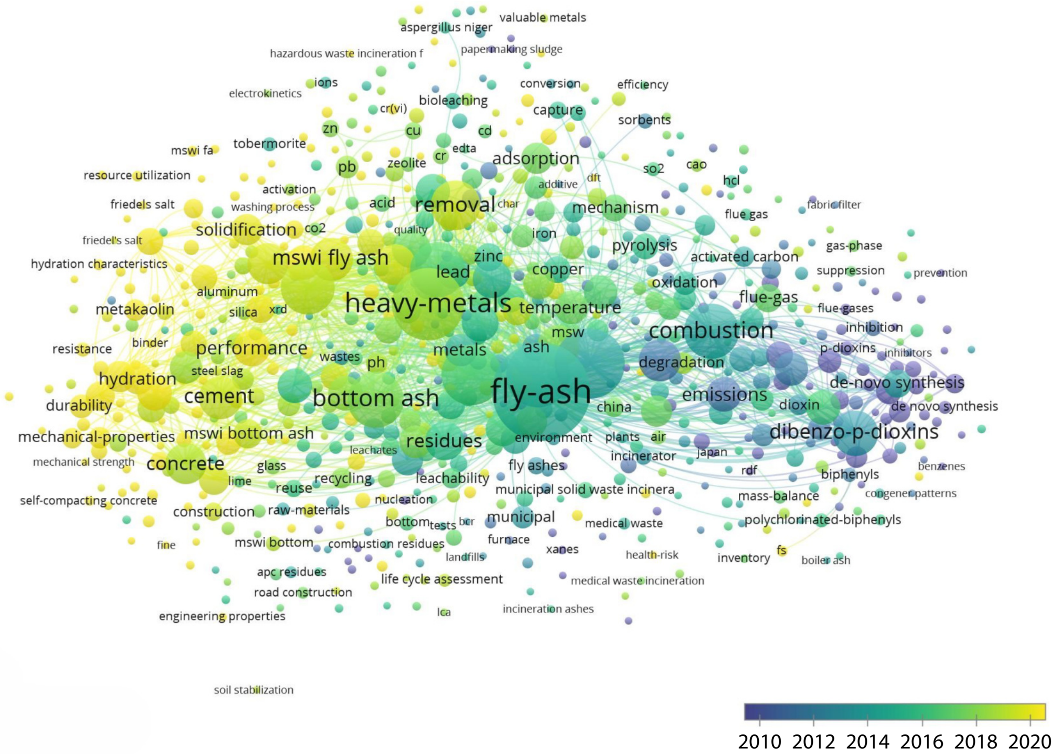

Fig. 2. Keyword co-occurrence network for research related to MSWIR.

various MSWIR components, the resource utilization of MSWIR can be maximized.

Therefore, this paper aims to review the research progress on the resource utilization of MSWIR in cement-based materials. The physical properties and chemical compositions of MSWIR from different sources, regions, and treatment processes are systematically categorized. On this basis, it integrates performance test data of cement-based materials containing MSWIR from various literature sources. The impact of MSWIR on the rheological properties, mechanical properties, and heavy metal stabilization effects of cement-based materials is elucidated. Additionally, the advantages and disadvantages of incineration bottom ash (IBA) and incineration fly ash (IFA) in various resource utilization approaches are compared, providing guidance for the harmless, stable, and resource-efficient utilization of MSWIR.

2. Physicochemical properties and pretreatment methods of MSWIR

MSWIR can be primarily categorized into incineration bottom ash (IBA) and incineration fly ash (IFA) based on their collection locations. IBA mainly consists of non-combustible heterogeneous mixtures, accounting for approximately 80% of the total weight of MSWIR, and is classified as general solid waste. IFA refers to the residues collected in the flue gas purification system and heat recovery system, accounting for about 20% of the total MSWIR and is classified as hazardous waste[12-14].

2.1. Physicochemical properties of IFA

2.1.1. Physical properties

IFA appears as a fine powder in shades of ash white or dark gray. It typically exhibits spherical, rod-like, or fibrous morphologies and is characterized by low moisture content, wide particle size distribution, high porosity, rough surface texture, and a large specific surface area. The particle size predominantly ranges from 4 to 100 μm, with a specific gravity between 2.1 and 3.0[15]. Table 1[16-23] summarizes the particle size and specific surface area measurements of IFA reported by various researchers. It is evident that the median particle size of IFA primarily falls between 5 and 60 μm, with specific surface areas ranging from 300 to 700 $m^2\ kg^{-1}$. Fig. 3[24] presents the scanning electron microscope (SEM) images of IFA. Fig. 3a reveals that IFA predominantly exhibits a fibrous structure, with loosely aggregated particles, a rough surface texture, high porosity, and a large surface area, which may facilitate the leaching of heavy metals. Fig. 3b distinctly shows spherical glass phases, with numerous small particles adhering to the surfaces of IFA particles. These fine glass beads confer high chemical reactivity and adsorption capacity on IFA, which may be one of the reasons for the elevated heavy metal content in fly ash.

2.1.2. Chemical properties

The composition of IFA is complex, primarily consisting of small amounts of unburned organic matter and incombustible inorganic matter, and is rich in dioxins, heavy metals, and a significant quantity of soluble salts[25-37]. Table 2[27–31,34-37] summarizes the chemical composition of IFA as reported by various researchers, indicating that IFA mainly comprises CaO, SiO_2, K_2O, Fe_2O_3, and Cl. However, due to variations in waste composition, incinerator types, air pollution control devices, flue gas purification processes, and actual incineration temperatures, the content of these substances exhibits sig-

Table 1. Fly ash particle size and specific surface area.

Researcher (Year)	Particle size (D_{50}, μm)	Specific surface area (m^2 kg^{-1})	Sample description
Shen et al. (2024)[16]	28.30	-	-
Zhang et al. (2024)[17]	55.19	-	-
Jing et al. (2023)[18]	19.67	349	Water washing
Doudart et al. (2016)[19]	38.00	-	-
Lee et al. (2011)[20]	-	640	Water washing
Song et al. (2008)[21]	18.85	-	-
Sun et al. (2023)[22]	60.00	-	-
Li et al. (2021)[23]	-	431	-

Note: -, Unspecified in literature.

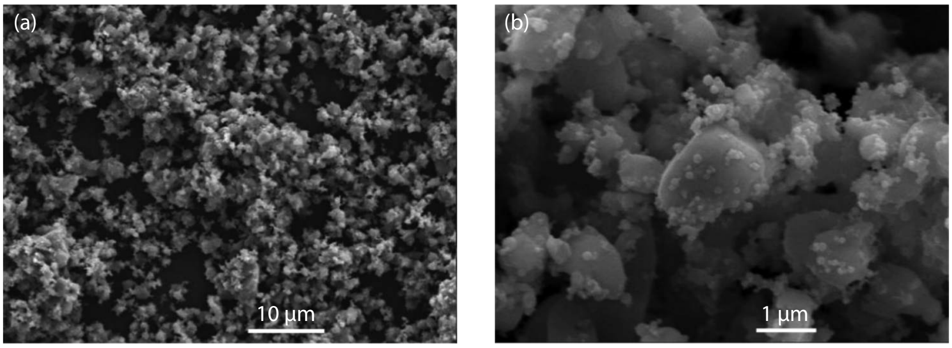

Fig. 3. SEM images of IFA samples at various magnifications: (a)×2000, (b)×15000. Reproduced with permission from Ref. [24].

Table 2. Chemical composition of IFA (wt%).

Region	Sample	CaO	Na_2O	Al_2O_3	SiO_2	SO_3	K_2O	Fe_2O_3	Cl	MgO
Italy[27]	No	19.90	5.09	3.65	9.48	23.60	3.76	0.79	12.80	1.70
Shenzhen[28]	Water Washing	40.18	10.24	3.88	18.29	6.03	4.31	0.81	-	2.48
USA[29]	Drying	38.30	3.07	5.88	18.80	5.15	1.60	4.10	3.27	1.76
USA[30]	Drying	37.40	3.53	2.37	7.85	8.56	2.40	2.23	-	2.18
USA[30]	Drying	54.90	3.59	2.37	3.93	5.54	2.37	0.12	-	0.98
France[31]	Water Washing	26.00	1.30	10.90	37.20	-	1.20	1.95	0.20	2.50
Wuhan[34]	Drying	44.31	8.55	2.30	5.58	6.31	4.59	1.34	16.57	1.50
Japan[35]	No	54.31	4.36	2.10	4.02	-	2.82	0.80	19.78	2.44
Poland[36]	-	3.30	0.06	12.60	28.59	1.00	2.22	8.03	-	1.45
Canada[37]	No	55.47	0.41	0.17	1.79	-	0.49	0.15	-	-

Note: -, Unspecified in literature; No, No pretreatment.

nificant regional differences[38].

During the incineration process, heavy metals carried by waste materials become concentrated in IFA after passing through the flue gas purification system, resulting in IFA containing substantial amounts of heavy metal ions such as Cd, Pb, Sb, Cr, Zn, and Ni. These heavy metal ions pose potential, persistent, and severe environmental pollution risks[39–42]. Table 3[31–35,39–42] compiles the measurement results of toxic heavy metal content in IFA from different regions, indicating that the levels of toxic heavy metals in IFA far exceed the limit values. Additionally, studies have indicated that dioxins in IFA are highly toxic, with a toxicity 130 times greater than cyanide and 900 times greater than arsenic[25], resulting in IFA being classified as hazardous waste in multiple countries[43].

2.2. Physicochemical properties of IBA

2.2.1. Physical properties

IBA typically appears in black-brown or cement-gray colors, and predominantly exists in granular form with particle sizes ranging from 0.1 to 100 mm[44]. The primary components of IBA are metals and minerals, giving it the potential for use in the production of ceramics and construction materials[14,45–49].

2.2.2. Chemical properties

Table 4[12,14,50–55] consolidates the empirical data on the chemical composition of IBA, revealing that the primary components of IBA are oxides such as CaO, SiO_2, Al_2O_3, and Fe_2O_3. Notably, compared to IFA (refer to Table 2), IBA contains higher levels of oxides such as Al_2O_3, SiO_2, and MgO.

Table 3. Heavy metal content in IFA (m kg^{-1}).

Region	Sample	Zn	Pb	Cu	Cd	Cr	As	Ba	Ni	Sb
France[31]	Water Washing	1046	4107	581	110	332	20	1586	52	378
	No	5677	786	704	90	183	-	-	237	442
Singapore[32,33]	Water Washing	7238	990	976	117	202	-	-	365	792
	-	3090	488	309	76	76	15	661	56	143
Wuhan[34]	Drying	-	1450	450	5671	170	530	-	-	-
Japan[35]	No	9322	1850	500	181	142	12	239	38	557
China[39]	-	6170	690	156.5	87	22.5	-	-	11	-
Spain[40]	Drying	449	1026	330	60	242	<25	412	93	372.
Germany[41]	-	3900	1300	7200	373	463	-	1500	122	2500
Fuzhou[42]	Drying	7880	822	337	204.5	118	-	-	30	-
Limit value	-	300	240	200	0.8	350	40	-	190	-

Note: -, Unspecified in literature; No, No pretreatment.

Table 4. Chemical composition of IBA (wt%).

Researcher (Year)	CaO	Na_2O	Al_2O_3	SiO_2	SO_3	Fe_2O_3	Cl	MgO	ZnO	TiO_2	P_2O_5
Huang et al. (2023)[14]	9.70	1.90	13.80	56.70	0.40	6.10	-	2.90	-	-	-
Lim et al. (2023)[50]	53.12	0.66	13.81	7.94	2.04	7.39	1.77	3.03	0.81	1.98	5.69
Xiang et al. (2022)[51]	40.56	3.31	7.92	23.34	4.63	6.40	3.15	2.79	-	-	4.30
Kumar et al. (2023)[52]	26.14	-	9.94	34.04	7.54	13.09	0.90	2.29	-	-	-
Li et al. (2023)[12]	57.71	3.26	3.42	10.35	5.62	4.79	3.58	3.84	0.51	-	3.43
Wei et al. (2011)[53]	33.40	2.53	16.65	31.93	-	5.97	1.08	3.33	-	1.45	0.02
Liu et al. (2023)[54]	25.52	2.70	13.17	36.49	3.50	7.45	3.04	2.70	-	1.18	-
Lin et al. (2023)[55]	41.35	2.98	13.21	11.91	3.07	7.49	5.04	2.78	1.52	1.58	4.39

Note: -, Unspecified in literature.

Table 5[51,56-63] records the heavy metal content in IBA, showing that certain volatile heavy metals, such as Cd, tend to concentrate in IFA. Although IBA is generally considered a non-hazardous waste[52,64,65], when considering the use of IBA for landfill or construction materials, it is advisable to treat the contained heavy metals appropriately to ensure safety and harmlessness.

2.3. Pretreatment and modification

As previously mentioned, MSWIR contains a range of inorganic/organic impurities and toxic substances. Therefore, before reusing IFA and IBA in cement-based materials, it is generally necessary to employ various physical, chemical, and biological methods to separate heavy metals, soluble salts, and other compounds from IFA and IBA. This ensures that the final concrete products possess excellent engineering and environmental performance.

The current pretreatment methods for MSWIR, as shown in Fig. 4, mainly include three categories: solidification/stabilization, separation, and thermal treatment[66-69].

2.3.1. Solidification/stabilization

Solidification/stabilization[70-73] encompasses cement solidification, chemical stabilization (e.g., alkaline solution treatment, water treatment, acid solution treatment, etc.), and mechanochemical methods. It is currently one of the widely applied and effective treatment solutions. Cement solidification primarily immobilizes heavy metals within C-S-H and C-A-H gels through hydration reactions to prevent leaching[74]. However, in the long term, certain heavy metals such as Cr, Ni, As, and V may re-leach under complex environmental conditions (e.g., seawater, groundwater, and acid rain)[75]. The effectiveness of chemical stabilization depends on the reagents used. For instance, silicates can form C-S-H gels that

Table 5. Heavy metal content in IBA (mg kg^{-1}).

Researcher	Zn	Cu	Pb	Mn	Ni	Cr	Sn	Sb	Sr	Co	V	As
Xiang et al.[51]	1326	343	186	200	84	108	-	233	-	759	100	185
Chen et al.[56]	5564	3481	1931	1098	475	474	217	188	179	97	29	21
Forteza et al.[57]	600	500	2700	280	180	900	960	-	-	-	-	13
Garcia-Lodeiro et al.[58]	2747	1697	759	743	71	277	273	-	549	-	-	-
Jurič et al.[59]	967	-	-	574	-	281	-	78	394	16	36	5
Yang et al.[60]	418	206	37	467	16	127	57	Nd	-	5	20	96
Assi et al.[61]	4280	2420	3740	700	-	320	-	-	200	-	-	-
Lynn et al.[62]	4044	3071	1641	921	182	398	-	253	379	50	167	50
Wei et al.[63]	1720	919	-	1147	183	444	142	90		54	61	23

Note: -, Unspecified in literature.

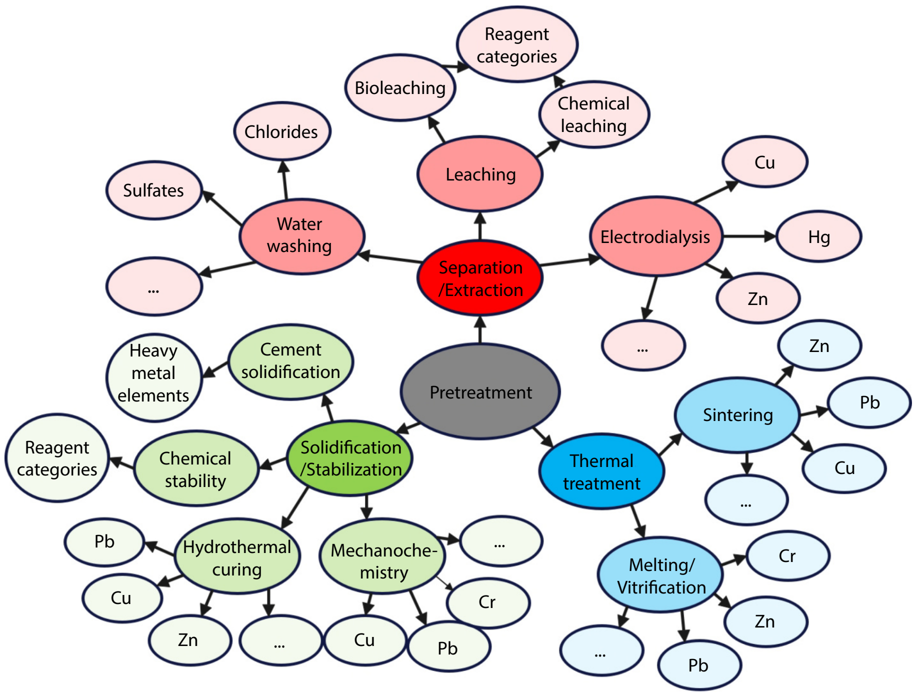

Fig. 4. Diagram of pretreatment methods for MSWIR.

effectively encapsulate heavy metals like Zn, Pb, and Cu. Mechanochemical methods employ various mechanical forces such as collision, compression, shear, and friction to induce changes in the physicochemical properties of solid particles, thereby activating or accelerating reactions between solid particles[75].

2.3.2. Separation

Separation can be achieved through methods such as water washing, leaching, and electrodialysis. Water washing can remove soluble substances, such as chlorides and sulfates[55,76], along with reactive ions like calcium and alkali metals that promote hydration, resulting in decreased ash reactivity during the hydration process. Additionally, water washing may lead to the formation of insoluble compounds, such as carbonates, on the particle surfaces, creating a passivation layer that inhibits water penetration and limits further reactions within the ash. In practice, water washing often requires a combination with other methods to achieve optimal results. Besides water washing, leaching involves the use of chemical or biological leaching agents to facilitate the removal of heavy metals. However, the effectiveness of different leaching agents varies for different heavy metals, and the efficiency is influenced by factors such as the pH value of the leaching agent, time, and temperature[77]. Electrodialysis operates on the principle of suspending ash in a solution placed in the electrodialysis chamber. An electric field is applied across the cell, causing metal ions to migrate towards the electrodes according to their charge[78]. This method effectively extracts Cu, Hg, and Zn, but is less effective for Cd, Pb, and especially Cr[79]. Research by Ebert et al.[80] confirms that electrodialysis can improve IFA performance. However, this process is significantly affected by factors such as density, temperature, mixing state, and pH value, and it has high power consumption, limiting its economic benefits[80].

2.3.3. Thermal treatment

Thermal treatment (such as sintering, melting, and vitrification[81,82]) can effectively remove toxic metals and persistent organic pollutants at high temperatures, showing high removal efficiency for heavy metals like Zn, Pb, and Cr. Sintering is the most common thermal treatment method, with process temperatures typically ranging from 900 to 1200 °C. The sintered products formed from MSWIR have low porosity and high strength, which helps to prevent heavy metal leaching. Heavy metals such as Zn, Cr, Pb, and Cu primarily appear in oxidized forms, exhibiting excellent solidification capacity. Melting/vitrification temperatures generally range from 1100 to 1500 °C, during which organic components in MSWIR decompose, including dioxins, while inorganic components transform into glass slag through crystalline phase changes. The difference between melting and vitrification lies in that the latter requires glass-forming additives or other solid wastes to form a homogeneous liquid phase material, which is then cooled to form an amorphous, homogeneous single-phase glass[83]. The heat and temperature required for melting mainly depend on the composition of MSWIR; acidic oxides (e.g., SiO_2, P_2O_5, TiO_2) generally increase the melting temperature, while basic oxides (e.g., Na_2O, K_2O, MgO, CaO, MnO_2) generally decrease the melting temperature[84]. Theoretically, different heavy metals can be eliminated by adjusting the temperature due to their varying evaporation temperatures. However, this process can generate harmful gases and consume a significant amount of energy.

Through a series of pretreatment processes, MSWIR can be utilized as a partial raw material for cement concrete production, thus achieving its harmless treatment and resource utilization. Currently, as illustrated in Fig. 5, the resource utilization of MSWIR in cement-based materials is mainly as a raw material for cement production[85,86], supplementary cementi-

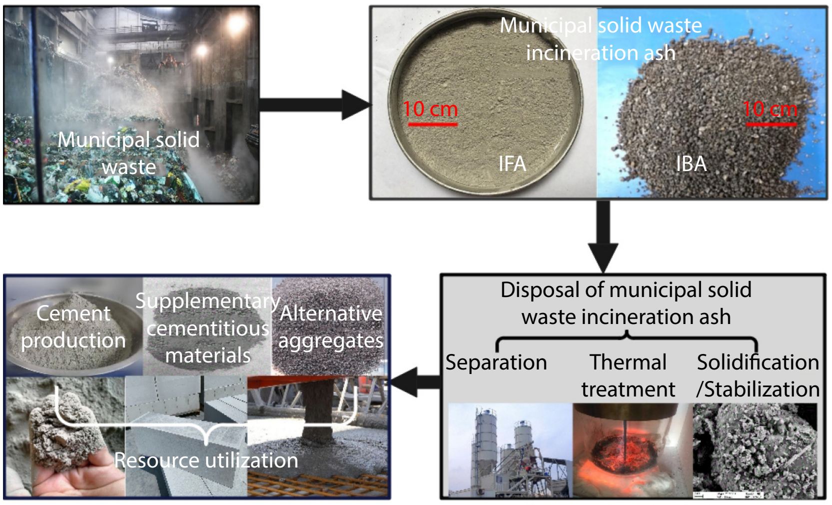

Fig. 5. Process of MSWIR resource utilization.

tious material[30,87,88], or a substitute for concrete aggregates[49,89].

3. MSWIR as a raw material for cement production

Cement occupies a central role in the construction industry, with global production significantly increasing from 940 million tons in 1970 to 4.1 billion tons in 2018[90]. In 2022, China's annual cement production reached 2.1 billion tons[2]. The large-scale cement industry brings about immense energy consumption, mineral resource pressure, and environmental pollution issues[91]. In light of this, many researchers have begun exploring the potential of using MSWIR as a raw material for cement production to seek more environmentally friendly and sustainable building material solutions.

3.1. Feasibility analysis

3.1.1. Feasibility in chemical composition

As previously mentioned, the small particle size of IFA endows it with certain pozzolanic activity, and its chemical composition is similar to that of cement, making it a potential raw material for cement. Ashraf et al.[37] produced eco-cement using MSWIR at 1100 °C, and the experiment found that its compressive strength could reach up to 55 MPa with heavy metal leaching concentrations below the permissible limits, confirming the feasibility of using IFA in cement production. This finding aligns with the experimental conclusions of Lam et al.[92] and Singh et al.[93]. IBA is also considered a potential alternative raw material for cement[94,95]. Kleib et al.[96] found that adding IBA to the raw material in clinker production does not affect the mineral composition and does not significantly alter the compressive strength of the cement paste. Clavier et al.[97] suggested that moderately replacing washed IBA as a cement raw material is a good choice. However, existing studies[96,98,99] generally agree that the feasibility and proportion of IBA as a cement raw material mainly depend on its composition, particle size, and the type of target cement. Thus, many studies[100-103] have shifted their focus to the discrete components of IBA. IBA is primarily composed of ceramics, glass, and slag, with the SiO_2 content in glass being relatively high, ranging from 66% to 75%[100,104]. Additionally, ceramics and slag contain abundant Al_2O_3 and Fe_2O_3[100,105]. These substances can replace bauxite, limestone, iron slag, sand, and clay in cement kiln feed to provide various elements for clinker. The lower heavy metal content and large production volume of IBA offer advantages for cement production, but factors such as particle size and other components must also be considered. In summary, both IFA and IBA have their unique advantages and limitations, and each has the potential to become an ideal alternative raw material for cement production.

3.1.2. Feasibility in technical processes

Due to its inherent CaO content, MSWIR facilitates the production of CaO in the cement manufacturing process without the urgent need for extensive limestone calcination, thereby significantly saving energy and mineral resources compared to conventional cement production methods[52]. Moreover, the high-temperature conditions of cement production are well-suited for the co-processing of MSWIR: when the calcination temperature of the cement kiln reaches 1400–1500 °C, dioxins in MSWIR are completely decomposed, and other heavy metals and harmful substances are encapsulated in the clinker[85,94,106]. This process not only facilitates the production of cement but also enables the disposal of MSWIR[37,107-109], thereby reducing carbon emissions and enhancing the utilization efficiency of energy and resources. Currently, the technology for using MSWIR in cement production is well-established, as shown in Fig. 6. The co-processing technology of fly ash in cement kilns[110-112] not only utilizes the inorganic salts in fly ash but also converts them into cement products, thereby improving economic benefits.

3.2. Effect on mechanical properties

The use of MSWIR in cement production has a minimal impact on the mineral composition of the cement but significantly affects the hydration performance and mechanical properties of the cement clinker. Both IFA and IBA have similar mechanisms of influence on cement-based materials, related to their components and heavy metals. Fig. 7[11,96,109,110,113-116] shows the impact of different IFA/IBA incorporation levels on the 28-day compressive strength of cement-based materials

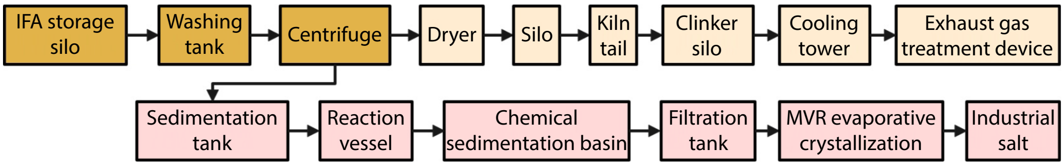

Fig. 6. IFA co-processing technology in cement kilns.

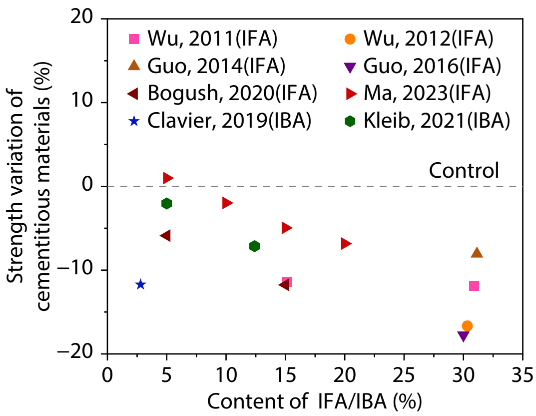

Fig. 7. Effect of MSWIR content on the 28-day strength of cement-based materials.

from various studies. To eliminate the influence of variations in raw materials and sample preparation across different studies, the strength variation between the experimental group with IFA/IBA and the blank control group was used for comparative analysis. It can be observed from the figure that the 28-day compressive strength of cement-based materials generally shows a linear decreasing trend with increasing incorporation of IFA or IBA, indicating a consensus that the incorporation of IFA/IBA weakens the strength of cement-based materials. In view of this phenomenon, there are various viewpoints on the reasons, which can be broadly summarized into three points:

(1) The incorporation of MSWIR lowers the temperature of solid-state reactions, inhibiting the formation of C_3S. Specifically, $CaCO_3$ reacts with SiO_2, Al_2O_3, and Fe_2O_3 to form C_2S, C_3A, and C_4AF in a cement kiln, among which C_2S will only react with calcium composite oxides to form C_3S at a certain temperature[116]. When MSWIR, containing chlorides, alkalis, and other flux components, is incorporated, the required temperature for the solid-state reaction decreases, which is insufficient for the formation of C_3S. Consequently, the generation of C_3S is inhibited, leading to a deficiency of C_3S in the clinker and a reduction in compressive strength[97,117-119]. As the incorporation level increases, the C_3S content further decreases, and the compressive strength gradually diminishes.

(2) The inhibitory effect of trace elements in MSWIR on C_3S. In other words, the increased content of trace heavy metals in IFA/IBA may lead to the destabilization and degradation of C_3S, thereby reducing the mechanical properties of the clinker[120]. Research has found that Cd and Zn decrease the compressive strength of cement-based materials, while Cr increases their early strength[120]. Additionally, when the P_2O_5 content exceeds 0.5%, it can lead to a reduction in C_3A production, resulting in a decrease in cement strength[121].

(3) Insufficient calcium oxide in MSWIR leads to poor cement strength development. In detail, the lack of adequate calcium oxide content hinders the production of calcium silicate, resulting in low hydration levels and negatively affecting mechanical properties.

To further elucidate the mechanism by which MSWIR affects strength development, the strength of cement-based materials incorporating MSWIR at different curing ages was analyzed. Similarly, the strength variation between the experimental group and the control group is used as the analysis parameter to eliminate the influence of variations in raw materials and sample preparation across different studies. According to Fig. 7, the compressive strength of cement-based materials decreases approximately linearly with increasing incorporation of IFA or IBA. Therefore, the ratio of strength variation to incorporation amount is plotted on the vertical axis, as shown in Fig. 8[96,116-118,121], to approximately eliminate the influence of incorporation amount. As illustrated, the strength of the experimental group incorporating IFA/IBA is consistently lower than that of the control group. However, with increasing curing age, the negative impact of IFA/IBA on cement strength gradually diminishes, indicating that the compressive strength of cement-based materials progressively approaches that of the control group, which is also related to the influence of IFA/IBA on the formation of C_3S and C_2S. In detail, trace elements in IFA/IBA will inhibit the formation of C_3S[119,122], which hydrates rapidly and is crucial for the early strength development of cement. Therefore, when the C_3S content is insufficient, the negative impact of MSWIR on the early strength of cement-based materials is more pronounced.

3.3. Effect on workability

Fig. 9[86,118,121,123,124] shows the effect of IFA/IBA on the setting time of cement. When the content of IFA/IBA is less than 20%, the initial and final setting times of cement containing

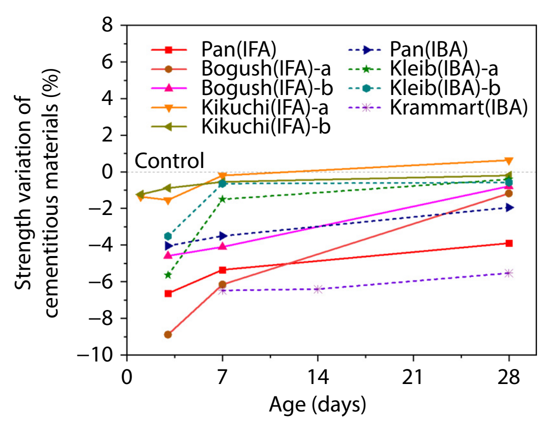

Fig. 8. Effect of MSWIR on the strength development of cement-based materials.

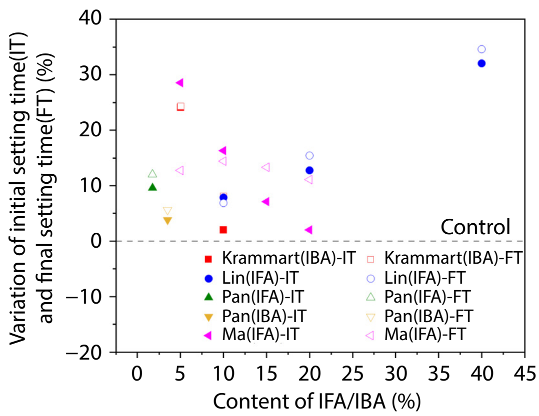

Fig. 9. Influence of MSWIR dosage on cement-based materials setting time.

IFA/IBA increase by approximately 10% compared to the control group. This could be due to several factors: The lower reactivity of MSWIR may delay the hydration reaction; heavy metal ions in MSWIR, such as Cr, Cd, and Cu, can promote the hydration of C_3S, while Zn and Pb can retard it[86], thus affecting the setting time. In other words, the amount of C_3S and C_2S generated is the main factor affecting the setting time. Kikuchi et al.[117] reduced the setting time by controlling the C_3S and C_2S contents in the clinker. Insufficient C_3S content or excessive C_2S content can both extend the setting time[117,118], which is consistent with the earlier analysis on the reduction in compressive strength. In addition, when the incorporation rate of MSWIR exceeds 20%, some researchers believe that the cement will be diluted, resulting in a lower degree of clinker hydration compared to pure cement, thereby increasing the setting time[123].

Although the incorporation of MSWIR has certain negative impacts on the performance of cement clinker, cement products based on MSWIR still exhibit significant application potential. For instance, Zhang et al.[125] prepared a green concrete entirely made from MSWIR (eco-cement produced from IFA as binder and IBA as aggregate) and found that the strength and heavy metal leaching of this concrete met standards. Ghouleh et al.[126] prepared eco-cement by adding calcium hydroxide into MSWIR, which constituted 96% of the total composition, and found that the eco-cement clinker showed strength development comparable to ordinary Portland cement after carbonation, consistent with the conclusions of Ashraf et al.[37]. Additionally, the strength of eco-concrete further increased with aging, exhibiting excellent freeze-thaw resistance and shrinkage resistance, thereby proving the potential of eco-cement as an independent binder for commercial concrete products after carbonation.

Moreover, MSWIR has broad applications in non-silicate cement systems, such as sulfoaluminate cementitious material (SACM), which is notable for its early strength, rapid hardening, high efficiency in heavy metal immobilization, and environmental friendliness. Li et al.[127] successfully prepared SACM with excellent strength by synergistically using IFA, aluminum dross (AD), and other solid wastes. The dioxins in IFA were decomposed during the thermal co-treatment, and heavy metals were effectively immobilized with almost no leaching. Therefore, the thermal co-treatment of IFA and AD has certain development potential, effectively pretreating and manufacturing SACM as a sustainable cementitious material. In addition, Mao et al.[128] developed a high-performance, environmentally friendly solid waste source (SWS) sulfoaluminate cementitious material by calcining at 1270 °C for 30 min. The primary raw materials included 35% washed pre-treated IFA and two types of industrial solid waste. The study found that, under the same curing time, the strength of SWS sulfoaluminate cementitious material was superior to that of similar fly ash-based cementitious materials. Besides, the SWS sulfoaluminate cementitious material exhibited excellent immobilization of heavy metal ions, with the leaching concentrations of eight heavy metal ions at various ages far below the standard limits.

3.4. Comparison of IFA and IBA as cement raw materials

Through the aforementioned analysis, it is comprehensively found that both IFA and IBA, due to their physicochemical properties, reduce the mechanical strength of cement clinker and delay its hydration process. However, each has its own set of advantages and disadvantages in application. IFA, with its fine particle size and suitable mineral composition, possesses a certain degree of pozzolanic activity, making it appropriate for the production of cement clinker. Yet, its higher content of heavy metals limits its application, making heavy metal treatment a key challenge in the use of IFA for cement clinker production. On the other hand, IBA exhibits a lower heavy metal content and a more favorable environmental profile compared to IFA. However, the application of IBA is constrained by its inherent composition, although its larger particle size offers the potential for the separation of its components. Consequently, current research suggests that discrete components of IBA could be employed as substitutes for traditional raw materials in the preparation of clinker, demonstrating greater application potential.

4. MSWIR as a supplementary cementitious material

Currently, MSWIR is not only employed as a raw material for cement production but also as a supplementary cementitious material for resource recovery. This application has been substantiated in numerous studies[67].

4.1. Feasibility analysis

Current research on the utilization of IFA as a supplementary cementitious material is quite extensive. IFA consists of ultrafine particles smaller than 100 μm with a composition similar to that of cement, exhibiting properties akin to those of traditional supplementary cementitious materials such as fly ash and ground granulated blast furnace slag. The incorporation of IFA will affect the compressive strength, setting time, and workability of cementitious materials[129]. Xie et al.[130] prepared cement-based materials by replacing 15% of the cement with IFA, and found that although the compressive strength decreased, it remained above 32 MPa. This finding is similar to those of Yan et al.[131] and Garcia-Lodeiro et al.[58].

In terms of IBA, Zhang et al.[132] demonstrated that incorporating bulk IBA as an additive in concrete increased the 90-day compressive strength by 18.4% compared to ordinary Portland cement concrete, thereby proving the feasibility of using IBA as a supplementary cementitious material. Cheng et al.[133] developed eco-friendly engineered cementitious composites (ECC) by partially replacing cement with bulk IBA. The results showed significant differences in mechanical strength and strain-hardening properties between ECC containing IBA and traditional ECC. This discrepancy may be attributed to the varying components within IBA, some of which may not be suitable as supplementary cementitious materials. Tang et al.[103] studied the discrete components of IBA, revealing that ceramics and glass contribute most to the reactivity of IBA and are more suitable as supplementary cementitious materials, whereas slag has lower reactivity and higher heavy metal content, making it a less ideal choice. Magnuson et al.[100] also confirmed that the glass and ceramic components in IBA exhibit superior strength and beneficial elemental composition, demonstrating strong pozzolanic activity. Therefore, through discretization, IBA may have its unique advantages in this application.

4.2. IFA as a supplementary cementitious material

4.2.1. Effect on mechanical properties

Fig. 10[60,134-145] illustrates the impact of IFA as a supplementary cementitious material on the compressive strength of cement-based materials. As observed from Fig. 10, at low replacement levels (less than 10%), the weakening effect of IFA on strength is not significant, and in some cases, it can even lead to an increase in strength. Regarding this phenomenon, some studies suggest that due to its fine particle size, IFA, when ground, helps fill the voids formed during the hydration reaction, enhancing the density of the material and thereby improving compressive strength to a certain extent. However, as the IFA content increases, a significant reduction in the compressive strength of the cement-based materials is observed. Based on current research, the reduction in compressive strength can be attributed mainly to two factors: (i) the low pozzolanic activity of IFA. Some studies indicate that the activity of IFA, when mixed with cement, is only about 57%[146], and this low activity limits the effective cementitious action of IFA, thereby affecting the formation of hydration products and the density of the microstructure; (ii) a high content of IFA interferes with the normal hydration process of cement paste, directly leading to a decrease in compressive strength. Additionally, many researchers[23,143,147] believe that heavy metals in IFA can adversely affect compressive strength. For example, aluminum can undergo oxidation to produce hydrogen gas, causing material expansion, increased porosity, and even cracking.

Based on an in-depth investigation into the effects of IFA content on the strength of cement-based materials, this paper uses a quadratic curve to fit experimental data from numerous studies, resulting in an empirical formula that reveals the trend of strength reduction as IFA content increases, as shown in Fig. 10. Therefore, to ensure sufficient compressive strength, the IFA content should be controlled within a certain threshold range, currently suggested to be around 20%[60,141,142,145,148].

To enhance the practical utilization of IFA, researchers have proposed various modification strategies. For instance, the use of alkali activation technology and the selection of appropriate alkali activators can effectively enhance the compressive strength of the material[30,149,150]. Additionally, carbonation helps to remove chlorides from IFA, which may be beneficial for the development of material strength[134,151].

4.2.2. Effect on workability

Fig. 11[25,60,134-136,144] reveals the varying effects of IFA as a supplementary cementitious material on the setting time. As shown in the figure, different studies show significant variation in experimental data regarding the effect of IFA content on the setting time of cement-based materials. This variability is primarily due to the complex mechanisms by which IFA influences setting time, involving multiple variables such as the heavy metal components and chloride ion content in the fly ash.

On one hand, chlorides in IFA, such as NaCl and KCl, can react with C_3A in cement to form water-insoluble hydrated calcium chloroaluminates, which further interact with $Ca(OH)_2$ to form water-insoluble calcium chlorate. This series of reactions reduces the concentration of $Ca(OH)_2$ in the liquid phase, thereby accelerating the hydration of C_3A in the cement[135], ultimately shortening the cement setting time. On the other hand, heavy metal ions in IFA play a key role, with heavy metal cations (such as Zn^{2+}, Pb^{2+}, Cu^{2+}) and anions (such as Cl^-, SO_4^{2-}, NO_3^-) having different effects on set-

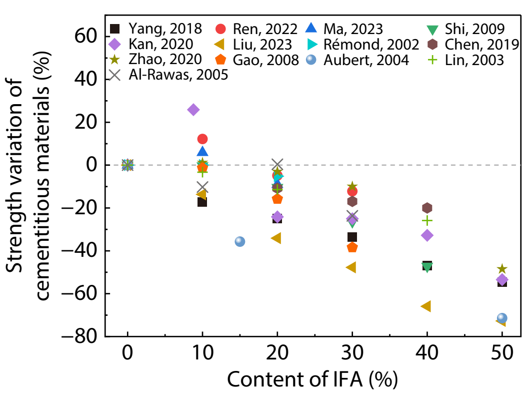

Fig. 10. Effect of IFA content on the compressive strength of cement-based materials.

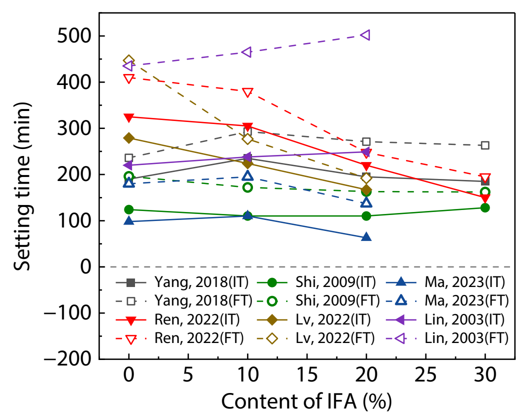

Fig. 11. Effect of IFA content on setting time.

ting time. Heavy metal cations can delay the setting time and hydration of cement, whereas anions have the opposite effect[136].

Additionally, pretreatment methods may also affect setting time. For instance, carbonation might form a carbonated boundary layer on particle surfaces, causing $CaCO_3$ agglomeration, slower particle dissolution, and delayed hydration processes[134]. In summary, understanding the specific impact of IFA on the setting time of cement-based materials requires comprehensive consideration of various factors and an analysis of specific experimental conditions.

4.2.3. Heavy metal leaching

When introducing IFA as an admixture, it is crucial to not only focus on its impact on the engineering properties of cementitious materials but also pay close attention to its environmental safety implications. During incineration, heavy metals undergo a series of processes including high-temperature volatilization, chemical transformation, migration with flue gas, condensation, deposition, and flue gas purification, ultimately becoming concentrated in the IFA[152]. If these heavy metals are not properly managed, they could lead to severe environmental pollution. It is known that IFA has a high specific surface area, making it more prone to contact with external solutions compared to coarse particles, which could result in the release of adsorbed heavy metals through surface interactions[153].

However, when IFA is incorporated into cement or concrete systems, these heavy metals can be effectively immobilized. The immobilization mechanisms mainly include two aspects: (i) heavy metal ions are tightly encapsulated within the micro-network formed by C-S-H gel, restricting their mobility[154,155]; (ii) heavy metal ions can be integrated into the silicate-aluminate network structure, achieving charge balance through the formation of M–Al chemical bonds, further enhancing their stability[154].

Fig. 12[60,135,137,138,144] summarizes the heavy metal leaching from cement-based materials containing IFA. Numerous studies consistently show that the short-term heavy metal leaching amounts from cementitious composites containing IFA comply with relevant standards. However, research on the long-term leaching behavior of heavy metals from such materials under service conditions is still insufficient and warrants further investigation and optimization.

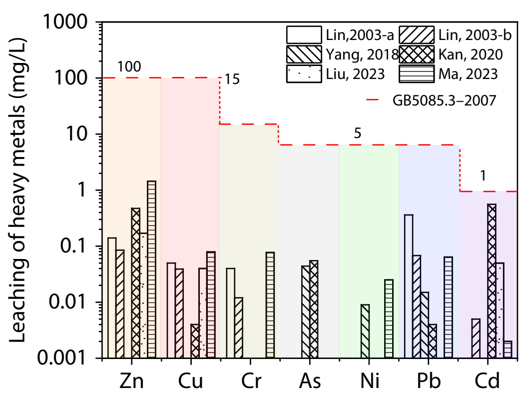

Fig. 12. Heavy metal leaching from cement-based materials containing IFA.

By reviewing the existing literature, the following characteristics of heavy metal leaching can be summarized: (i) the leaching processes of different heavy metal ions follow distinct mechanisms, and their leaching rates vary significantly. For example, Pb leaching is primarily controlled by diffusion, while Cu, Cr, and As leaching is governed by both diffusion and surface wash-off, and Ni leaching is mainly influenced by diffusion and dissolution[155]; (ii) the leaching rate of heavy metal ions from the material surface is a critical factor determining their leaching behavior[156]. In the early stages, when the material is not fully solidified, the surface structure is relatively loose, allowing heavy metal ions to diffuse to the surface easily, resulting in higher leaching rates and greater leaching amounts. As the material gradually solidifies and forms a highly dense structure, the leaching rate significantly decreases, and the leaching amount correspondingly reduces[155,156].

Given these characteristics, researchers have proposed various strategies to reduce heavy metal leaching, including pretreatment, pH control, and optimized curing methods[75,155]. Pretreatment can inhibit heavy metal leaching; for instance, melting/vitrification (thermal treatment) can transform IFA into vitrified slag, utilizing the dense crystalline structure within the glassy phase to effectively immobilize heavy metals, thereby preventing their diffusion into the solution and reducing leaching[75,81,82,157]. However, excessively high thermal treatment temperatures may have adverse effects. Studies have shown that increasing the melting temperature from 1230 °C to 1600 °C significantly decreases the immobilization rates of heavy metal ions such as Pb, Cu, and Zn, highlighting the importance of temperature on the effectiveness of heavy metal immobilization[157].

Additionally, carbonation can improve the pore structure of the material, reduce porosity, and thus decrease heavy metal leaching. Many researchers have found that although carbonation can reduce the leaching of heavy metals such as Na, K, and Ca, it may increase the leaching of Cu and Mg. This phenomenon may be related to the decrease in pH caused by carbonation, which deteriorates the stability of Cu, leading to increased Cu leaching[158,159]. It is important to note that excessive carbonation can cause microcracks, increasing leaching[158].

Besides, curing conditions are crucial for the solidification process of materials, and reasonable adjustments to curing schemes can effectively regulate heavy metal leaching. Liu et al.[138] compared the effects of standard curing, steam curing, and carbonation curing on leaching, finding that carbonation treatment had a significant effect on heavy metal immobilization. They hypothesized that this might be due to carbonation altering the pH of the pore solution in the material, which aligns with Wei et al.[160], who observed that in an alkaline environment, the leaching concentrations of Zn and Pb decrease as pH decreases. From these results, it can be inferred that pH may have a considerable impact on leaching, consistent with the viewpoint of Jiao et al.[153]. They emphasized that pH is crucial in the leaching of toxic heavy metals: under acidic conditions, heavy metals are more likely to leach into the solution, while in alkaline conditions, precipitation and adsorption mechanisms can effectively mitigate heavy metal leaching. Furthermore, it is important to recognize that variations in pH are closely related to the behavior of cations, amphoteric species, and oxygen-containing anions in metal compounds. Understanding these relationships can help elucidate how changes in pH influence the mobility of heavy metals in various environmental contexts.

4.3. IBA as a supplementary cementitious material

4.3.1. Effect on mechanical properties

Fig. 13[99,132,161-166] presents experimental data on the impact of IBA on the mechanical properties of cement-based materials. The figure indicates that the incorporation of IBA has a negative effect on the strength, similar to the phenomenon observed with cement-based materials containing IFA. This can be attributed to the following reasons:

(1) Interference with hydration reactions: The heavy metals, chlorides, and sulfates contained in IBA consume hydration products and impede the hydration process, thereby weakening the mechanical properties of the material[60,167]. Specifically, chlorides react with calcium ions in the cement, reducing the number of calcium ions available for hydration; sulfates react with aluminates to form calcium sulfoaluminate, consuming hydration products; magnesium combines with silicates to form insoluble magnesium silicates, reducing the effective silicate content; heavy metal ions such as Pb, Cr, and Cd react with silicates and aluminates to form insoluble or poorly soluble salts, which block capillary pores and hinder the formation of hydration products[136].

(2) Impact on material density: The oxidation reaction of metallic aluminum produces hydrogen gas, leading to volume expansion and cracking[23,147]. Metallic iron, free calcium oxide, and magnesium oxide may also have similar effects[168]. For example, free calcium oxide reacts with water to form calcium hydroxide, releasing a significant amount of heat. This causes local overheating and induces thermal stress, which can lead to cracks. Other studies have shown that the incorporation of IBA increases the total porosity and capillary porosity, resulting in decreased compressive strength. This phenomenon is likely closely related to the disruption of hydration reactions and the effects of volume expansion[163].

(3) Characteristics of IBA material and external factors: The particle size, reactivity, and incorporation amount of IBA directly influence its impact on material performance. Since the reactivity of IBA is lower than that of Portland cement, its addition results in a decline in mechanical properties. Notably, the glass and ceramic components in IBA significantly contribute to its reactivity. Therefore, it is essential to identify the material composition before use to ensure its reactivity is appropriate, thereby avoiding poor performance due to excessively low reactivity.

From Fig. 13, it is evident that the incorporation of IBA results in a significant reduction in the compressive strength of the material. Compared to Fig. 10, the extent of this reduction is more pronounced, especially at low replacement levels, indicating that IBA is less effective than IFA as a supplementary cementitious material. This underscores the need for further treatment of IBA or modifications in its specific utilization methods, such as employing discrete components of IBA.

4.3.2. Effect on microstructure

As previously mentioned, the reactivity of IBA is lower than that of Portland cement, resulting in insufficient cementitious capability. The incorporation of IBA hinders the hydration process and increases the setting time. Fig. 14 shows the SEM images of cement mortar; images (a) and (c) are of pure cement mortar at 3 d and 28 d of curing, respectively, while images (b) and (d) are of mortar with 30% IBA. From images (a) and (b), it can be observed that calcium hydroxide crystals and C-S-H gel are formed in the hydrated cement paste after 3 d of curing. However, the size of the calcium hydroxide crystals in image (b) is smaller than that in image (a), indicating that the addition of IBA slows down the hydration reaction[164]. At 28 d of curing, images (c) and (d) show that more C-S-H gel is produced in the mortar, leading to a denser microstructure of the matrix. Nevertheless, the differences between the two images are also evident; the structure in image (c) is more compact, while image (d) shows a lower degree of hydration, with some unhydrated IBA still present, resulting in reduced mechanical properties of the material.

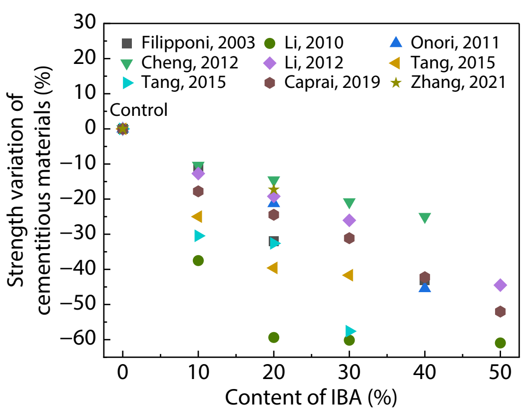

Fig. 13. Effect of IBA content on the compressive strength of cement-based materials.

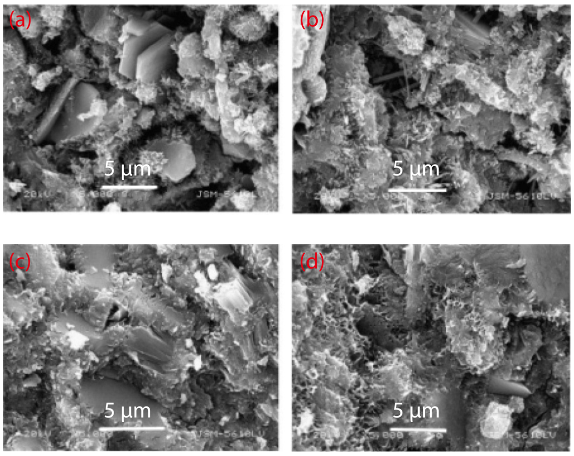

Fig. 14. SEM images of cement paste: (a) C0 3 d; (b) C3 3 d; (c) C0 28 d; (d) C3 28 d. Reproduced with permission from Ref. [164].

This may be due to the formation of abundant silica gel when IBA is mixed with water. This gel absorbs water and accumulates between unhydrated cement particles, gradually enveloping them, thereby hindering normal hydration and increasing the water demand for standard consistency.

In summary, due to the low reactivity of IBA and the interference of certain chemicals with the hydration reaction, the hydration of cement-based materials containing IBA is delayed, resulting in increased setting time and higher water demand for standard consistency. This is consistent with the findings of Li et al.[164], Alnezami et al.[169], and Yang et al.[60].

4.3.3. Heavy metal leaching

The heavy metal content of IBA is lower than that of IFA, as corroborated by numerous studies[52,64,65]. However, when utilizing IBA as a supplementary cementitious material, attention must be paid to its heavy metal leaching to avoid adverse environmental impacts.

Table 6[59,161,164,165,170-172] summarizes the current heavy metal leaching levels from cement-based materials containing IBA. The data reveal that the leaching concentrations in most experiments meet the relevant standards, within environmentally acceptable limits. However, there are instances where heavy metal concentrations exceed the standards. For example, Tang et al.[165] found that using untreated IBA led to the leaching of Cu, Sb, chlorides, and sulfates beyond the standard limits. They hypothesized that the leaching of Cu is related to organic matter and confirmed this through loss on ignition tests. Subsequently, they discovered that washing and high-temperature treatment of IBA reduced the leaching of these substances to within acceptable limits[170]. This phenomenon is not isolated; many researchers have found that IBA may only meet leaching requirements after pretreatment[52,171,172].

4.3.4. Development trends

Based on the analysis of the mechanical properties and workability of cement-based materials using IBA as a supplementary cementitious material, it was found that bulk IBA is not very suitable as a supplementary cementitious material. However, due to the good composition of IBA, current research has begun to focus on the discrete components of IBA. Tang et al.[103] studied the activity of various separated components of IBA and found that glass and ceramics in the discrete components of IBA exhibited the highest activity, suggesting that these components might be the main contributors to the cementitious activity of IBA. This view is supported by Magnuson et al.[100], who further suggested that the less active substances in IBA (such as minerals and slag) could be used as fillers or as replacements for raw cement materials (due to their suitable composition).

Fig. 15[103] shows the microstructural differences in cement mortar prepared by replacing 20% of ordinary Portland cement (OPC) with different discrete components of IBA.

Table 6. Heavy metal leaching from cement-based materials containing IBA.

Researcher (Year)	Content	Test method	Leaching results
Jurič et al. (2006)[59]	15%	k0-INAA	Leaching concentration meets the limit values.
Li et al. (2010)[161]	50%	TCLP	Leaching concentration meets the GB-5085.3—2007 standard.
Li et al. (2012)[164]	30%	TCLP	Leaching concentration meets the GB-5085.3—2007 standard.
Tang et al. (2015)[165]	10%–30%	NEN 7383	Except for Cu and Sb, the other leaching meets the SQD standard.
Tang et al. (2016)[170]	30%	NEN 7383	Leaching is below the SQD standard limit values.
Qiao et al. (2008)[171]	90%	NEN 7375	Leaching concentrations are within the detection limits.
Saikia et al. (2015)[172]	25%	EN12457-2	Leaching concentration meets the DIN 38414-S4 standard.

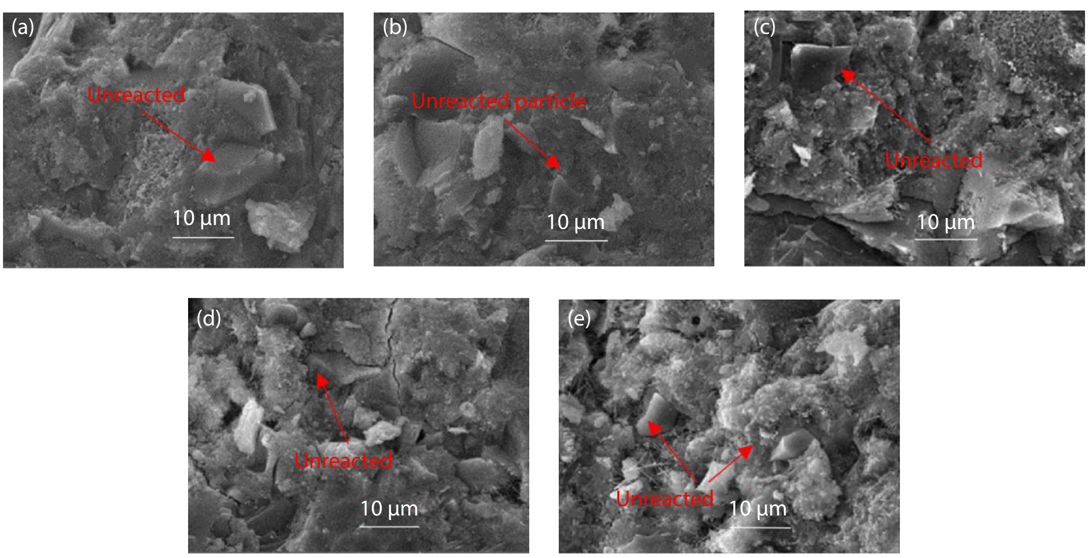

Fig. 15. Microstructure of cement mortar prepared by replacing 20% of ordinary Portland cement with (a) IBA-glass, (b) IBA-ceramic, (c) IBA-mineral, (d) IBA-slag I, and (e) IBA-slag II. Reproduced with permission from Ref. [103].

The analysis results indicate:

(1) Microstructural density: The mortar samples with IBA-glass and IBA-ceramic have a dense internal structure without significant micro-cracks or large voids. In contrast, the samples with IBA-mineral, IBA-slag I, and IBA-slag II have a loose internal structure with cracks and voids.

(2) Component-matrix bonding performance: In mortar samples with IBA-glass and IBA-ceramic, the unreacted IBA components are tightly bonded to the cement matrix, showing that the two components actively participate in cement hydration, forming stable hydration products that enhance mechanical properties and durability. Conversely, in mortar samples with IBA-mineral, IBA-slag I, and IBA-slag II, the unreacted components are loosely bonded, indicating lower hydration activity, incomplete transformation, or weak chemical bonding with the matrix.

The mechanical performance of the aforementioned materials is consistent with the microstructural analysis. The 28-day compressive strength of IBA-glass and IBA-ceramic reached 91.6% and 97.3% of the control (pure cement mortar), respectively, and their 90-day strength even reached 104.4% and 102.9%. In contrast, the 28-day strength of IBA-slag I and IBA-slag II achieved only 76.5% and 74.6%, respectively, similar to the mechanical performance of bulk IBA as a supplementary cementitious material. In summary, the utilization of IBA as a supplementary cementitious material shows that discrete components may have greater potential.

4.4. Comparison of IFA and IBA as a supplementary cementitious material

Through discussions on mechanical performance, workability, and microstructure, it was found that at the same dosage, IFA may have a better impact on mechanical strength compared to bulk IBA. The potential application of discrete components of IBA may be greater than that of bulk IBA. Overall, IFA has advantages due to its higher activity and smaller particle size, but it requires pretreatment because of its high heavy metal content. Although IBA has fewer heavy metals, it has larger particle sizes and more complex compositions, thus screening and grinding are recommended before use.

Based on the above analysis, MSWIR can be utilized as both a raw material in cement production and a supplementary cementitious material (SCM) in concrete applications, though with distinct production processes and mechanisms that affect concrete properties. When used as a raw material, MSWIR undergoes high-temperature processing during cement manufacturing, where it is blended with other raw materials and subjected to calcination, resulting in chemical changes that enhance binding properties. In contrast, when utilized as an SCM, MSWIR is finely ground to increase its reactivity and is often processed at lower temperatures to preserve its pozzolanic properties. The chemical composition of MSWIR plays a crucial role in both scenarios; as a raw material, its characteristics significantly influence the strength and durability of the final product, while as an SCM, it enhances hydration reactions with calcium hydroxide produced during cement hydration. Furthermore, the physical properties of MSWIR, such as fineness and morphology, impact the water-cement ratio and overall workability of concrete mixes. Overall, understanding these differences is essential for optimizing concrete formulations that incorporate MSWIR, ensuring enhanced performance and sustainability in construction applications.

5. MSWIR as a substitute for concrete aggregates

One of the primary pathways for the resource utilization of MSWIR is as a substitute for concrete aggregates. Through certain treatment or preparation techniques, MSWIR can partially or completely replace concrete aggregates.

5.1. Feasibility analysis

Due to its small particle size, IFA has the potential to replace fine aggregates; however, direct replacement results in a significant decline in mechanical properties[173]. Consequently, the strategies for transforming IFA into high-quality aggregates have been widely discussed, as illustrated in Fig. 16[174-176]. Chen et al.[174] successfully produced standard-compliant lightweight aggregates, demonstrating the suitability of IFA as a raw material: the product exhibited low heavy metal leaching and the concrete strength met the requirements for lightweight structures, underscoring the potential for industrial-scale production of IFA aggregates. Additionally, studies by Hwang et al.[177], Han et al.[67,176], and Ferraro et al.[175] have also confirmed the effectiveness of IFA in aggregate preparation.

IBA exhibits characteristics of low heavy metal content, high strength, and large particle size, which are similar to traditional concrete aggregates, making it a perfect substitute for aggregates[57,178]. Relevant research findings are illustrated in Fig. 17[48,179,180]. Yao et al.[181] revealed the impact on cement mortar performance by directly replacing aggregates with IBA: although the mortar's flowability decreased with increasing IBA content, early strength improved, and later strength slightly declined but remained within acceptable limits, with heavy metal leaching controlled at safe levels. This is consistent with the experimental conclusions of Huynh et al.[48], Shen et al.[182,183] and Ye et al.[184].

In terms of innovative aggregate preparation techniques, Tang et al.[179] utilized IBA to produce cold-bonded lightweight aggregates through granulation processes, which exhibited heavy metal leaching levels below standard limits but required further enhancement of mechanical properties. Yaphary et al.[180] applied these aggregates to precast lightweight concrete, demonstrating that despite a reduction in mechanical strength, the results still met the standards. Liu et al.[54] revealed that adding alkali activators during the IBA preparation process effectively enhanced the mechanical strength of the resulting aggregates, reduced water absorption, increased apparent density, and decreased heavy metal leaching, further confirming the potential and optimization pathways for IBA as a sustainable aggregate substitute.

5.2. Preparation of aggregates from IFA

5.2.1. Performance and influencing factors

Researchers have conducted pretreatment on IFA and various wastes and mixed them in specific proportions using differ-

Fig. 16. Aggregates prepared from IFA. Reproduced with permission from Refs. [174-176].

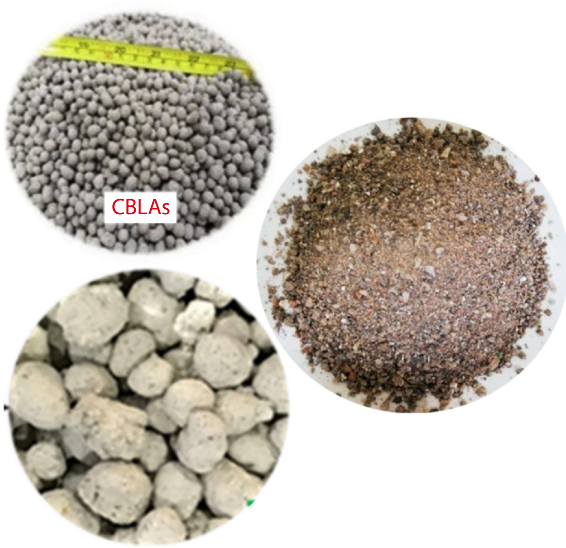

Fig. 17. Aggregates replaced/prepared with IBA. Reproduced with permission from Refs. [48,179,180].

ent materials and processes to produce aggregates with different characteristics. Table 7[67,174-177,185,186] summarizes key information from several studies, including the factors affecting performance such as raw materials for aggregates and sintering temperature, as well as performance indicators like bulk density, water absorption, and compressive strength of the aggregates. It should be noted that the first two compressive strength data refer to the compressive strength of cylinders, while the last three refer to the compressive strength of single particles. The overall analysis shows that aggregates derived from IFA generally have lower mechanical strength and higher water absorption rates than natural aggregates, indicating slightly insufficient comprehensive performance.

Analysis of existing literature reveals that the performance of aggregates is significantly influenced by the properties of raw materials, pretreatment methods, and preparation processes. To enhance the performance and application value of IFA aggregates, many researchers have explored these three dimensions. Chen et al.[174] and Hwang et al.[177] used reservoir sediments with good plasticity and suitable chemical composition as the main material for aggregates, with IFA serving as a flux additive. Although this combination can produce usable aggregates, the utilization efficiency of IFA is low, at only 30%. Han et al.[67,176] found that washing IFA with water can improve aggregate performance,

Table 7. Preparation of aggregates from IFA.

Researcher	Raw material	Sintering temperature (°C)	Performance		
			Bulk density (kg m^{-3})	Water absorption (%)	Compressive strength (Mpa)
Chen et al.[174]	IFA, RA, RS	1100–1200	593	7.6	6 (cylinders)
Hwang et al.[177]	IFA, RS	1070–1150	-	7.6–29	5.3–11.0 (cylinders)
Ferraro et al.[175]	IFA, GBFS, MS	CBP	1600–1870	-	1.3–10.9 (particles)
Han et al.[176]	IFA, bentonite	1060–1200	229–950	2.5–31	-
Han et al.[67]	IFA, bentonite	1100–1200	100–930	1–424	-
Lu et al.[185]	IFA, IBA, RS	1000–1200	300–2250	1.58–26	0.2–7 (particles)
Colangelo et al.[186]	IFA, cement, lime	CBP	1000–1600	7–16	1.3–6.2 (particles)

Note: CBP, Cold bonding pelletization; -, Unspecified; RA, Reaction ashes; RS, Reservoir sediments; GBFS, Granulated blast furnace slag; MS, Marble sludge.

reduce heavy metal leaching, and increase IFA utilization to 50%. They suggest that washing removes chlorides and other solvents, affecting the sintering reaction. Currently, artificial aggregate processes are mainly divided into sintering and cold bonding. The sintering method used by Hwang et al.[177] promotes the formation of glassy aggregate particles at high temperatures, enhancing structural density and aiding in the stable solidification of heavy metals. However, the amount of IFA needs to be precisely controlled, as its role as a flux may affect sintering conditions, and the process is energy-intensive. Colangelo et al.[186] increased the utilization rate of IFA to 70% using the cold bonding granulation method, with the highest single- particle strength reaching 6.2 MPa. However, this method's drawbacks include longer preparation times and lower efficiency.

Currently, there is limited research on the impact of IFA aggregates on the performance of cement concrete. However, existing literature indicates that although IFA aggregates have relatively poor performance, the concrete prepared with them still meets standard requirements[174,177,186]. Chen et al.[174] successfully prepared concrete samples with a compressive strength of 40 MPa using IFA aggregates. Experiments found that the bond strength between IFA aggregates and surrounding mortar is greater than the particle strength, leading researchers to believe that the true controlling factor for concrete strength is the strength of the mortar and its arching effect on the aggregates, a view shared by Hwang et al.[177].

5.2.2. Heavy metal leaching

Due to the high content of heavy metals in IFA, the leaching of heavy metals from IFA aggregates is a major concern for researchers. The leaching behavior is related to the amount of IFA, pretreatment methods, and aggregate preparation methods. As mentioned, sintering forms a glassy layer on the particle surface, solidifying the heavy metals[177]. However, excessive amounts of IFA can exacerbate the expansion of aggregates, creating numerous cracks and voids, which may lead to increased heavy metal leaching. Therefore, it is essential to control the amount of IFA or pretreat it. Han et al.[67] found that water-washing pretreatment of IFA increased the heavy metal stabilization rate by 109%. During the cold bonding granulation process, due to the absence of high temperatures, the glassy layer cannot form on the surface of the particles, inhibiting the effective solidification of heavy metals. As a result, the leaching of heavy metals depends on the pretreatment, binder type, and granulation method. For example, using cement as a binder can solidify heavy metals through cementation, reducing leaching[175]. Additionally, two-step granulation can increase the amount of cement used, further enhancing the solidification of heavy metals[186].

5.3. Preparation of aggregates from IBA

5.3.1. Performance and influencing factors

IBA coarse particles can be directly substituted for natural aggregates, whereas fine particles are commonly co-processed with other materials to fabricate aggregates. Table 8[49,89,179,187-194] compiles studies on the preparation of aggregates from fine IBA particles, highlighting that the first five entries denote the compressive strength of cylindrical specimens, and the subsequent seven entries indicate the strength of individual particles. The data analysis reveals that aggregates derived from IBA generally have higher water absorption rates. When compared to incinerator fly ash (IFA) aggregates, IBA aggregates exhibit a lower density, yet their overall strength is found to be on par.

The performance of incinerator bottom ash (IBA) aggregates is influenced by factors such as raw materials, pretreatment, and preparation methods. To enhance the performance of IBA aggregates, most researchers incorporate supplementary cementitious materials to strengthen the binding of aggregate components, increase compactness, and improve aggregate performance, thereby suppressing the leaching of heavy metals. Tang et al.[188] improved the fine IBA particles (<2 mm) by using nanosilica as a binder and adding polypropylene fiber material, resulting in enhanced performance of the IBA aggregates. Li et al.[89] compared the effects of crushed

Table 8. Preparation of aggregates from IBA.

Researcher (Year)	Raw Material	Size (mm)	Performance		
			Bulk density ($kg\ m^{-3}$)	Water absorption (%)	Compressive strength (Mpa)
Tang et al. (2017)[187]	IBA, OPC, FA, PSA, PPF, WAS	4–16	881±46	17–25	5.64–9.93 (cylinders)
Tang et al. (2018)[188]	IBA, FA, PPF, PSA, NS	4–18	883±40	19	7.56–9.90 (cylinders)
Liu et al. (2022)[189]	IBA, GGBFS/FA, PPF	4.75–16	996±61	13–14	2.83–5.03 (cylinders)
Liu et al. (2022)[49]	IBA, GGBFS/FA, PPF, OPC	4.75–16	1078±12	10.52–11.08	7.40–7.80 (cylinders)
Li et al. (2023)[89]	IBA, GGBFS, OPC, FA	2.36–19	946±32	15.3–18.4	4.35–7.99 (cylinders)
Cioffi et al. (2011)[190]	IBA, OPC, LM, CFA	5–20	-	11.13–13.46	1.9–4.5 (particles)
Tang et al. (2019)[179]	IBA, OPC, GGBFS/FA	2.36–14	740±50	19.3–24.6	1–2.3 (particles)
Giro-Paloma et al. (2019)[191]	IBA, RH	-	-	1.7–16	1.4–6.6 (particles)
Tang et al. (2020)[192]	IBA, CSW, GGBFS	5–14	870±40	17–27	0.3–2 (particles)
Liu et al. (2022)[193]	IBA, GGBFS/FA, OPC	-	-	3.99–14.02	3–4 (particles)
Li et al. (2023)[89]	IBA, GGBFS, OPC	2.36–19	946±32	15.3–18.4	1.78–3.48 (particles)
Song et al. (2024)[194]	IBA, OPC, SIF	4–15	758±124	22.81–36.23	0.5–5.1 (particles)

Note: OPC, ordinary Portland cement; GGBFS, ground granulated blast furnace slag; FA, fly ash; WAS, washing aggregate sludge; PPF, polypropylene fiber; CSW, concrete slurry waste; NS, nanosilica; LM, lime; CFA, Coal fly ash; SIF, sisal fiber; RH, rice husk.

granulated blast-furnace slag and fly ash as cementitious materials on the performance of IBA aggregates. The experiments revealed that the group with fly ash had the lowest porosity, the lowest water absorption rate, and the highest particle strength, possibly due to the addition of fly ash improving the particle gradation curve and increasing the compactness of the aggregates. Due to the energy-saving advantages of cold bonding technology, many researchers have adopted this method for aggregate preparation[49,187,189]. Aggregates prepared by this method require curing similar to cement specimens, making the curing method crucial for the performance of the aggregates. Liu et al.[49] and Manikandan et al.[195] conducted research on the curing methods, finding that high-temperature curing promotes hydration, shortens curing time, reduces porosity, and enhances mechanical properties.

5.3.2. Impact on the performance of cement-based materials

In Huynh et al.'s study[48], natural sand was replaced with fine IBA particles, and it was found that as the proportion increased, the porosity and water absorption of the mortar specimens also increased, leading to a decrease in flexural and compressive strength. This indicates that the incorporation of IBA resulted in structural loosening and a decline in mechanical properties. The SEM images in Fig. 18 also confirm the above conclusion. It can be seen that the control specimen has a dense microstructure, but as the substitution rate of IBA increases, the SEM images show a less uniform microstructure with higher porosity and more microcracks. In addition, Yao et al.[181] used a wet pretreatment to remove non-ferrous metals from IBA and then used it as a fine aggregate substitute in mortar. The results showed that as the substitution ratio of IBA increased, the fluidity of the mortar decreased, and the porosity increased. Although the initial strength was enhanced, the flexural and compressive properties still showed a slight downward trend in the later stage. Fig. 19 shows the SEM images of cement mortar specimens at 28 d by Yao et al.[181], where Fig. (a) contains no IBA, and Figs. (b–d) contain 75% IBA. It was observed that the microstructure without IBA showed better formation of C-S-H gel. In Fig. (b), besides the C-S-H gel, blocky substances were also observed. Fig. (c) reveals C-A-S-H substances that can make the microstructure more compact, and Fig. (d) shows fine particles alongside calcium hydroxide, which may be beneficial to strength based on upon comprehensive analysis. Both sets of studies attribute the increase in porosity and water absorption to the inherent porous nature and high water absorption characteristics of IBA, which is consistent with the views of Shen et al.[182,183] and Ye et al.[184]. However, the mechanical properties showed the opposite trend. In Fig. 18, the generation of voids and cracks results in significant performance degradation, attributed to the inherent properties of aluminum and IBA aggregates. In contrast, Fig. 19 shows the removal of most heavy metals and chlorides, leading to a limited decrease in material performance.

Many researchers have demonstrated that the substitution of natural aggregates with IBA aggregates affects the properties of concrete, but within an acceptable range. This impact is derived from the inherent properties of IBA aggregates, such as porosity, density, particle shape, and mechanical strength. When the replacement rate is low, the low-density and high-porosity IBA aggregates can increase the total porosity of the concrete. However, their internal curing and pozzolanic effects may enhance the hydration of the paste, leading to a denser structure that counteracts the porous nature of IBA aggregates[89,182,183]. Additionally, the rougher surface of IBA aggregates compared to natural aggregates can form a good bond with the cementitious matrix, strength-

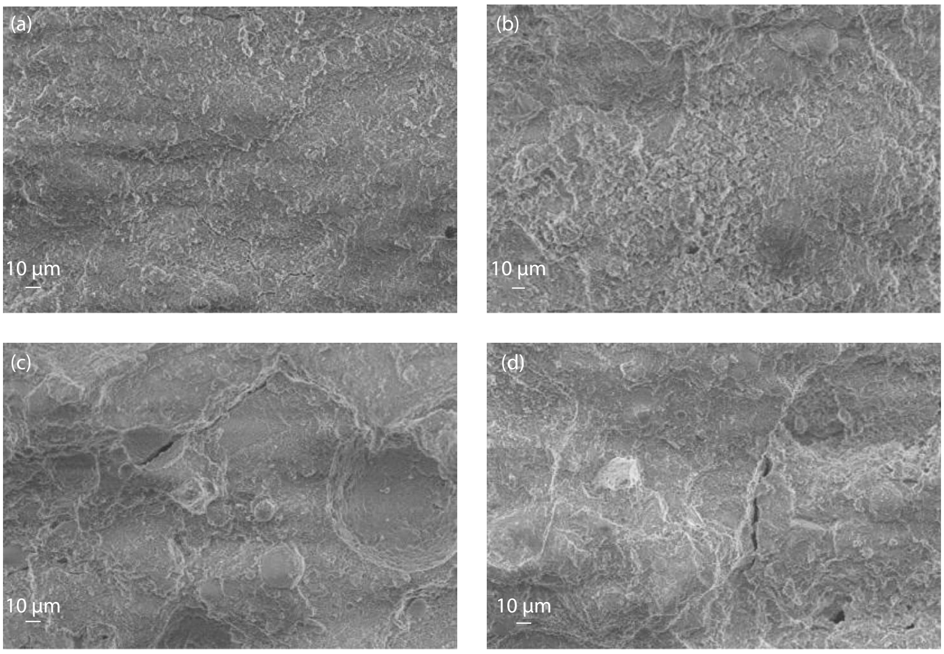

Fig. 18. Impact of IBA aggregates on cement mortar and concrete: (a) 25% IBA; (b) 50% IBA; (c) 75% IBA; (d) 100% IBA. Reproduced with permission from Ref. [48].

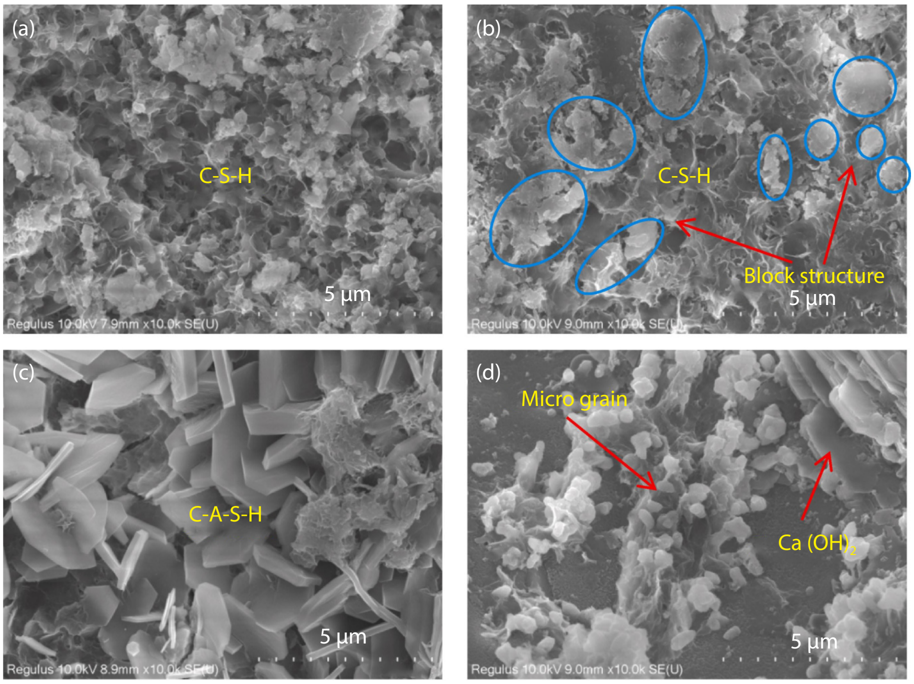

Fig. 19. SEM images of mortar containing (a) 0% IBA, (b–d) 75% IBA. Reproduced with permission from Ref. [181].

ening the interfacial transition zone and thereby benefiting the mechanical strength of the concrete[89,189]. As the replacement rate increases, the porosity of the concrete can increase rapidly, affecting the compactness of the structure, increasing the proportion of harmful pores, reducing mechanical strength, and increasing water absorption, which affects various properties of the cement-based materials[189]. However, a comprehensive review of existing studies indicates that the impact of IBA aggregates on the performance of concrete is relatively minor, and their properties still meet the requirements for use[182,183,189,196].

5.4. Comparison of IFA and IBA as aggregates

Based on the current research findings, it has been analyzed that IFA is unsuitable for direct use as an aggregate due to its smaller particle size. However, it shows certain feasibility as a raw material for aggregate preparation, though the leaching of heavy metals from the aggregate must be fully considered. With its low heavy metal concentration and suitable physicochemical properties, IBA offers more flexible utilization options. It can be directly substituted for aggregate or used as a raw material for the preparation of artificial aggregate.

6. Conclusions

This paper systematically reviews the chemical composition of MSWIR from different regions and the properties of cement-based materials containing MSWIR. It discusses the advantages and disadvantages of various resource utilization pathways for MSWIR, investigates the challenges faced in using MSWIR as a mineral resource for producing cement-based materials, and analyzes the possible causes. The main conclusions are as follows:

(1) IFA is primarily composed of CaO, SiO_2, and Fe_2O_3. Its heavy metal content exceeds the standards set for building materials, necessitating pretreatment methods to mitigate the adverse ecological impacts. In contrast, IBA has a chemical composition similar to IFA but with relatively higher contents of Al_2O_3, SiO_2, and MgO, and lower heavy metal content, posing a lesser environmental impact. The physicochemical characteristics of MSWIR exhibit significant regional features influenced by various factors, including waste composition, incinerator type, air pollution control systems, flue gas purification processes, and the actual operating temperature curve of the incinerator.

(2) MSWIR has the feasibility for producing cement clinker in terms of chemical composition and technical process. However, the cement clinker produced from MSWIR shows a significant decrease in strength, particularly in early strength, and an approximately 10% extension in initial/final setting times. The primary reason is that MSWIR inhibits the formation of C_3S, delaying cement hydration.

(3) When used as a supplementary cementitious material, the impact of MSWIR on reducing strength and delaying hydration intensifies with increasing dosage. This is mainly due to the low pozzolanic activity of MSWIR and the foaming effect of internal metallic aluminum. However, the small particle size of IFA helps fill the pores formed during hydration, increasing density. To ensure product quality, the IFA content should be controlled within a certain threshold range, currently suggested to be around 20%.

(4) The performance of MSWIR and its derivatives as concrete aggregates is influenced by the properties of the raw materials, pretreatment methods, and preparation processes. Generally, they have higher porosity and water absorption rates compared to natural aggregates, resulting in slightly inferior comprehensive performance. However, this adverse impact is within an acceptable range, and the performance of concrete products meets usage requirements.

(5) IFA and IBA have distinct resource utilization strategies in the construction field, although both can be utilized in cement production and as supplementary cementitious materials. Notably, the discrete components of IBA may have greater utilization potential than bulk IBA. For concrete aggregate applications, IFA tends to be converted into artificial aggregates, while IBA shows dual possibilities of direct replacement and raw material conversion. Each contributes to the sustainable development of the construction industry with its unique physicochemical properties.

(6) Heavy metal leaching is a critical issue that needs to be addressed in the resource utilization of MSWIR. When applied in cement concrete preparation or as cement raw materials, the encapsulation effect of C-S-H gel and the aluminosilicate network structure can effectively stabilize the heavy metals. Numerous studies indicate that the heavy metals in MSWIR generally meet standards in the short term (e.g., 90 d), potentially alleviating their environmental hazards. However, further in-depth research is needed to understand the long-term leaching behavior of heavy metals under complex environmental conditions.

Author contribution statement

Jiaxing Ma: Investigation, Methodology. **Zhennan Chen:** Data curation, Writing – review & editing. **Kequan Yu:** Visualization. **Shaoqin Ruan:** Writing – review & editing. **Ping Chen:** Conceptualization. **Ze Liu:** Investigation. **Songsong Lian:** Project administration, Writing – review & editing, Funding acquisition. **Jingming Cai:** Conceptualization, Project administration. **Neven Ukrainczyk:** Supervision. **Eddie Koenders:** Supervision. **Dongmin Wang:** Supervision, Methodology.

Declaration of competing interest

Dongmin Wang is the Editor-in-Chief for *Materials Reports: Solidwaste and Ecomaterials* and was not involved in the editorial review or the decision to publish this article. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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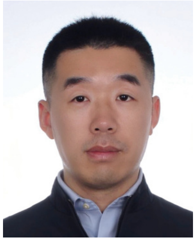

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