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Characterization of Concrete Incorporating Municipal Solid Waste: A Comprehensive Review

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ABSTRACT

Concrete production consumes large quantities of natural aggregate, water and Portland cement, while municipal solid waste creates an escalating disposal burden for urban regions. The incorporation of municipal solid waste-derived materials in concrete therefore joins two engineering objectives: reduction of landfill demand and partial substitution of virgin construction resources. This review examines the characterization of concrete incorporating municipal solid waste (MSW), with focused on MSW incineration bottom ash, municipal solid waste incineration fly ash, waste glass, waste plastics and selected electronic-waste fractions. The literature on source variability, preprocessing, mix-design implications, fresh behavior, hardened mechanical performance, durability response and environmental safety. The review shows that MSW incineration bottom ash is the most technically developed MSW constituent for concrete, especially after aging, washing, ferrous and non-ferrous metal removal, crushing, sieving and carbonation. For normal-strength concrete, bottom ash used as fine aggregate or as a minor cementitious/binder component is most successful at replacement levels commonly below 20%, while higher replacement levels require density correction, water-demand compensation, pre-treatment and performance-based qualification. Fly ash from MSW incineration is more chemically problematic because of chlorides, sulfates, soluble salts, free lime, heavy metals and variable glassy phases; its use is therefore safer after washing, thermal treatment, vitrification, carbonation or immobilization within blended binders. Waste glass can improve packing and pozzolanic activity when finely ground, but coarse glass aggregate increases alkali-silica-reaction risk unless particle size, alkali content and supplementary cementitious materials are controlled. Waste plastics reduce density and thermal conductivity but normally reduce compressive, tensile and flexural strength because of low stiffness and weak interfacial transition zones. Across the literature, hardened properties and durability depend less on the label "municipal waste" than on particle size, absorption, deleterious phases, leaching potential, adhered contaminants and the interaction between the waste fraction and cement hydration. The most robust conclusion is that MSW can be incorporated into concrete when it is treated as an engineered secondary raw material rather than as an uncontrolled disposal residue.

1. INTRODUCTION

MSW is a heterogeneous stream generated by households, commercial premises, public institutions and urban services. It normally contains food residue, paper, cardboard, plastics, glass, textiles, wood, metals, inert fines and small quantities of hazardous or electronic materials. Conventional disposal by landfill creates long-term land occupation, leachate management, methane generation and public-health concerns [1,2,3]. Incineration with energy recovery reduces waste volume and mass, but it creates bottom ash, boiler ash, air-pollution-control residue and fly ash that require treatment before beneficial reuse [7,8,9]. In parallel, the concrete industry extracts enormous quantities of natural aggregates and manufactures cement at high energy and carbon cost. The idea of incorporating MSW into concrete is therefore not simply a waste-management option; it is a materials-engineering strategy whose success depends on whether the waste fraction can satisfy concrete performance requirements without creating unacceptable durability or environmental risk [14,16,18].

The phrase "concrete incorporating municipal solid waste" covers several different materials and must be interpreted carefully. The most studied stream is MSW incineration bottom ash, abbreviated in the literature as MSWIBA, IBA, BA or MIBA. Bottom ash is the coarse, granular residue discharged from the furnace grate. It contains glass, ceramics, mineral particles, slag-like phases, brick fragments, residual metals and unburned organic matter. Because it is granular, it is normally evaluated as fine aggregate, coarse aggregate, lightweight aggregate, mineral addition or, after grinding, a low-grade supplementary cementitious material [1,2,15,17,18]. MSW incineration fly ash is a finer and more reactive residue collected from flue-gas treatment systems. It has much higher concentrations of soluble salts, chlorides, sulfates, heavy metals and free lime, making it more difficult to use safely in reinforced concrete [3,4,5,6]. Non-incinerated MSW fractions such as waste glass, plastic, tire-derived constituents, paper sludge ash and e-waste plastics or printed-circuit-board particles have also been tested in concrete, but their behavior is governed by different mechanisms [25,33,39].

The major research question is not whether municipal waste can be physically mixed with concrete. The critical question is whether the resulting concrete satisfies structural, durability, environmental and economic requirements. Concrete must gain sufficient compressive strength, tensile resistance and stiffness; it must resist water ingress, chloride penetration, sulfate attack, carbonation, freeze-thaw cycling and alkali-silica reaction; and it must immobilize potentially toxic elements under expected service and end-of-life exposure conditions [18,20,44]. A waste concrete that reaches target compressive strength but exhibits high chloride leaching, high water absorption, delayed expansion or reinforcement corrosion risk cannot be considered technically successful. For this reason, characterization must include chemical composition, particle morphology, density, water absorption, contamination, hydration effects, mechanical properties, durability indicators and leaching performance.

2. MUNICIPAL SOLID WASTE CONSTITUENTS RELEVANT TO CONCRETE

The composition of municipal solid waste-derived concrete constituents is controlled by local waste composition, collection practice, incinerator technology, combustion temperature, air-pollution-control process and post-treatment. Bottom ash is generally dominated by silica, alumina, calcium oxide and iron oxide, with variable sodium, potassium, chloride, sulfate and residual metallic aluminum. The mineral fraction contains quartz, calcite, gehlenite, akermanite, hematite, magnetite and amorphous glassy phases. Its physical form is usually porous and angular, which increases water absorption and lowers particle density compared with natural sand or gravel [7,8,22]. These characteristics explain why untreated bottom ash often reduces workability and compressive strength: it absorbs mixing water, increases voids, introduces weak porous particles and creates a less dense interfacial transition zone around the aggregate [1,2,50].

Fly ash from MSW incineration is more complex than coal fly ash. It contains fine particulate matter captured from flue gas and often includes salts from acid-gas neutralization. Chlorides and sulfates are frequently high; zinc, lead, copper, cadmium and other metals may be elevated; and free lime or calcium hydroxide may cause high alkalinity [3,4,5]. These properties create both an opportunity and a risk. The tiny particles and reactive calcium-bearing phases can participate in hydration or filler effects, but soluble salts and metals can retard cement hydration, increase corrosion risk and create leaching problems [4,6]. The literature therefore generally treats MSWI fly ash as a material requiring pre-treatment before use in concrete, unlike many conventional supplementary cementitious materials that are already standardized.

Waste glass is another large component of municipal waste. It is mainly amorphous silica with sodium and calcium modifiers, and its behavior in concrete depends strongly on particle size. Coarse glass aggregate has smooth surfaces and low water absorption, which can improve workability but reduce bond. It also contains reactive silica that can trigger alkali-silica reaction when the glass particle size, pore solution alkalinity and moisture conditions are favorable [25,27,28]. When glass is finely ground, the risk of deleterious expansion decreases and pozzolanic reactivity increases because the glass powder reaction with calcium hydroxide to form additional calcium-silicate-hydrate. This dual behavior explains why glass sand replacement and glass powder cement replacement must be treated as separate technologies [26,27,29].

Waste plastics in municipal solid waste include polyethylene terephthalate, high-density polyethylene, low-density polyethylene, polypropylene, polystyrene and mixed packaging polymers. Plastics have low density, low elastic modulus, hydrophobic surfaces and poor chemical affinity with cement paste. They can reduce concrete density and improve certain insulation or impact-related properties, but they usually reduce CS, SPT, FS and MoE [32,33,34,36,39]. The reduction is caused by poor paste-plastic bonding, particle deformation under load, increased entrapped air and stress concentration at the plastic-paste interface. Surface treatment, fiber geometry, small replacement levels and optimized grading can reduce the loss but do not remove the fundamental stiffness mismatch [35,38,41].

Electronic waste and mixed plastic-glass-metal residues represent a smaller but technically challenging MSW fraction. E-waste may contain flame retardants, heavy metals, copper, glass fibers and thermoset resins. When used as aggregate, e-waste particles can reduce density and occasionally increase toughness, but their environmental suitability depends on leaching and contaminant control. For structural concrete, e-waste is less mature than MSWI bottom ash or waste glass. It is better viewed as a candidate for non-structural blocks, tiles, pavers and controlled precast products unless rigorous contaminant testing is completed [39,44].

3. PROCESSING AND CHARACTERIZATION REQUIREMENTS

Municipal solid waste cannot be incorporated into concrete as an undefined raw residue. The first requirement is physical processing. For MSWI bottom ash, typical steps include aging or weathering, magnetic separation of ferrous metals, eddy-current separation of non-ferrous metals, crushing, screening, washing and removal of oversized ceramics, glass shards or unburned organics. Aging allows metallic aluminum to oxidize and permits carbonation of alkaline calcium phases. Washing reduces chlorides, soluble sulfates and fine salts. Crushing and sieving create a more controlled grading, while metal removal reduces pop-outs and long-term expansion [17,21,22]. Without these treatments, bottom ash can generate hydrogen gas through aluminum corrosion in alkaline pore solution, leading to swelling and surface defects.

Chemical characterization must include major oxides, chloride, sulfate, loss on ignition, total organic carbon, metallic aluminum and trace elements. X-ray fluorescence is commonly used for oxide composition, while X-ray diffraction identifies crystalline phases. Thermogravimetric analysis and scanning electron microscopy help interpret hydration and microstructure. Leaching tests are necessary because the purpose of reuse is not only mechanical performance but also environmental safety [44,45,46]. A material with acceptable compressive strength may still fail regulatory acceptance if lead, zinc, copper or chloride leaching exceeds thresholds. Leaching should also be evaluated at different pH values because cementitious matrices are highly alkaline initially, but carbonation and end-of-life exposure can change pore solution chemistry. Physical characterization includes specific gravity, bulk density, water absorption, particle-size distribution, shape, friability and contamination. MSWI bottom ash often has lower specific gravity and higher water absorption than natural aggregate [1,2,50]. High absorption complicates mix design because part of the batch water is consumed internally by the ash particles. If absorption is not corrected, slump decreases and the effective water-to-cement ratio becomes uncertain. Pre-saturation, water correction or the use of superplasticizer can stabilize fresh performance. For plastic aggregate, density and particle shape are critical because light, flat particles segregate easily. For glass, particle angularity and size distribution influence packing, workability and ASR risk.Treatment of fly ash is more demanding. Washing removes chlorides and soluble salts, but it produces a contaminated wash water requiring treatment. Thermal treatment, vitrification and sintering can immobilize heavy metals and reduce solubility, but they consume energy and increase cost [5,12]. Chemical stabilization with cement, lime, phosphates or carbonation may reduce leaching. The practical question is whether the treatment process is less expensive and less environmentally burdensome than disposal. Consequently, fly ash incorporation is more credible where treatment infrastructure already exists or where the treated product replaces a high-impact binder fraction in controlled applications.Performance characterization should not stop at 28-day compressive strength. A proper program includes slump, air content, density, setting time, compressive strength at multiple ages, splitting tensile strength, flexural strength, modulus of elasticity, shrinkage, creep, water absorption, sorptivity, rapid chloride penetration or migration, carbonation depth, sulfate expansion, freeze-thaw scaling and leaching [18,19,20]. Different applications require different thresholds. Paving blocks, masonry units and non-reinforced mass concrete tolerate higher variability than prestressed members or marine reinforced concrete. This means municipal solid waste concrete should be qualified by performance class rather than by a universal replacement percentage.

4. MIX DESIGN AND FRESH PROPERTIES

The mix design of municipal solid waste concrete must compensate for lower particle density, high absorption, variable grading and weak interfaces. When MSWI bottom ash replaces fine aggregate, the mix generally requires additional water or pre-wetting to maintain slump. Because additional water can reduce strength and increase permeability, superplasticizers are often preferable. Fine bottom ash particles can also increase paste demand because of angularity and rough surface texture. If bottom ash replaces coarse aggregate, the resulting concrete may behave as lightweight or semi-lightweight concrete; density decreases, but strength and stiffness may decrease as well [1,2,50].

As a cement replacement, finely ground bottom ash can provide filler effect and limited pozzolanic or latent hydraulic activity. Its performance is lower and more variable than fly ash, silica fume or slag, but treatment can improve reactivity. Chemical activation and fine grinding increase surface area and promote reaction with calcium hydroxide [23]. Some studies show that replacement levels around 10–20% can satisfy strength and durability targets when bottom ash is processed and the mixture is optimized [18,19]. Higher replacement levels are possible for non-structural products, but they tend to require carbonation curing, activators or low water-binder ratios to offset slower hydration and lower intrinsic reactivity.

MSWI fly ash changes fresh behavior through its fine particle size, salts and heavy metals. Some soluble metal species retard cement hydration. Chlorides accelerate early reactions but raise corrosion concerns. High free lime can create rapid heat evolution and volume instability. Treated fly ash may behave as a filler or secondary binder, but untreated fly ash is rarely appropriate for reinforced structural concrete [3,4,6]. In blended cement systems, washing and stabilization are central because the goal is to reduce deleterious soluble phases before the ash enters the cementitious matrix [5].

Waste glass affects fresh concrete differently. Glass aggregate has low absorption compared with natural sand and bottom ash, so it may increase workability. Its smooth surface can reduce water demand but also weakens bond. Finely ground glass powder can increase water demand if angular and very fine, but it can also improve packing density. The balance depends on fineness, replacement level and admixture compatibility [25,26,27]. Waste plastic particles frequently reduce density and can increase workability when smooth and hydrophobic, but light particles can segregate or float during vibration. Proper grading and limited replacement levels are necessary to maintain uniform distribution [32,33,39].A recurring mistake in municipal waste concrete research is comparing mixtures at equal replacement by mass when the waste has a different density from the replaced constituent. For aggregates, replacement should often be volumetric. Replacing natural sand by an equal mass of low-density bottom ash or plastic changes total aggregate volume, paste volume and void structure. This can lead to misleading strength comparisons. A rigorous mix design should report both mass and volume fractions, effective water-binder ratio, aggregate moisture condition, absorption correction and admixture dosage. Without these details, reported hardened-property results are difficult to compare across studies.

5. HARDENED MECHANICAL PROPERTIES

Compressive strength is the most frequently reported hardened property and the first indicator of municipal waste concrete feasibility. For MSWI bottom ash used as coarse aggregate, early work showed that concrete with a characteristic 28-day strength of approximately 25 MPa could be produced, but the bottom ash aggregate had lower density, higher absorption and lower strength than natural gravel [1]. Later work confirmed that bottom ash can function as aggregate in normal-strength concrete when deleterious components are removed and the grading is controlled [2]. The strength reduction at high replacement levels is attributable to porous ash particles, weak aggregate strength, higher water demand and a less dense interfacial transition zone. At modest replacement levels, especially when bottom ash is used as fine aggregate or processed binder, compressive strength may remain within structural ranges.Processed bottom ash performs better than raw bottom ash. Aging reduces free metallic aluminum reactivity and carbonation stabilizes alkaline phases. Washing removes chlorides and soluble salts. Waterglass impregnation and similar surface treatments can densify porous particles and reduce absorption [21]. The literature suggests that well-treated MSWI bottom ash can be used at around 10–20% replacement with acceptable compressive strength, while untreated or high-volume replacement tends to produce larger reductions [18,19]. Vaičienė and Simanavičius reported that concrete with moderate bottom ash replacement showed acceptable or improved density and compressive performance in selected mixtures, illustrating that the optimum is not zero when ash particles improve packing or internal curing [19]. Alderete and colleagues designed a concrete mix containing processed MSWI ashes as 20% of the binder while maintaining strength and durability targets, showing the importance of processing and mixture optimization [18].Splitting tensile and flexural strengths generally follow compressive strength but are more sensitive to bond quality. Municipal waste aggregates with smooth surfaces, weak internal structure or hydrophobic behavior reduce tensile transfer across the paste-aggregate interface. Bottom ash particles are rougher than glass or plastic and may develop mechanical interlock, but their porosity and internal flaws reduce particle strength. Glass aggregate can reduce tensile and flexural performance because of smooth surfaces, though finely ground glass powder can enhance later-age paste strength through pozzolanic action [25,26,30]. Plastic aggregate causes larger reductions in tensile and flexural strength because the elastic modulus of plastic is much lower than mineral aggregate and because the cement paste does not bond chemically to hydrophobic polymer surfaces [33,34,39]. When plastic is used as fibers rather than aggregate, the effect can shift toward crack bridging and toughness improvement, but fiber distribution and aspect ratio become critical [38].Modulus of elasticity is consistently reduced when low-stiffness municipal waste aggregate is used. This is expected from composite theory: the stiffness of concrete depends strongly on aggregate stiffness and volume fraction. Bottom ash has lower stiffness than crushed stone; plastic has far lower stiffness; and porous lightweight ash behaves similarly to lightweight aggregate. A concrete may meet compressive strength requirements but exhibit reduced stiffness, which affects deflection, vibration and crack-width control. Therefore, municipal waste concrete should not be specified by compressive strength alone. Structural applications require modulus testing or conservative design values.Density changes are important because they influence dead load and classification. Bottom ash and plastic aggregate usually reduce density. This can be beneficial for lightweight blocks, panels and non-load-bearing elements. Lower density may also reduce thermal conductivity. Yet density reduction is often accompanied by higher absorption and lower strength. For municipal waste concrete, density should be interpreted together with porosity. A lower-density concrete is desirable only if it achieves the required strength, durability and dimensional stability.Shrinkage and creep deserve greater attention than they receive in many studies. High-absorption bottom ash can act as an internal curing reservoir, but it can also increase total porosity and drying shrinkage. Plastic aggregate may restrain or relieve shrinkage differently depending on particle geometry and stiffness. Glass powder can refine pore structure at later ages and may reduce permeability, but coarse glass aggregate can create weak interfaces. Because long-term deformation controls serviceability, municipal waste concrete intended for structural members should be evaluated beyond 28 days.

6. DURABILITY PROPERTIES AND HARDENED-PROPERTY

Durability is the decisive criterion for municipal solid waste concrete. Water absorption and sorptivity are usually higher when porous MSWI bottom ash replaces natural aggregate because ash particles contain interconnected pores and absorb water [1,2,50]. Higher absorption increases the risk of chloride ingress, sulfate ingress and freeze-thaw damage unless the paste is densified by low water-binder ratio, supplementary cementitious materials or surface treatment. Processed bottom ash can reduce this penalty. Waterglass impregnation, carbonation and washing lower absorption and improve particle stability [21]. When bottom ash is finely ground and used as a binder fraction, the durability response depends on whether filler and secondary reactions refine the pore network enough to offset ash porosity.Chloride penetration is a central concern, especially for reinforced concrete. MSWI residues can introduce chlorides directly, and porous ash particles can increase connectivity. Untreated fly ash and air-pollution-control residue are particularly risky because soluble chloride content may be high [3,5,6]. Bottom ash contains less chloride than fly ash but still often requires washing for reinforced applications. In optimized mixes, processed bottom ash at moderate binder replacement can achieve acceptable chloride resistance, particularly when low water-binder ratios and supplementary cementitious materials are used [18]. Waste glass powder can improve chloride resistance through pozzolanic pore refinement when finely ground, while coarse glass aggregate may increase interfacial porosity if bond is poor [26,29,30]. Plastic aggregate often increases chloride permeability because of weak interfacial zones and entrapped air, although reduced connectivity may occur in specially designed mixes with low replacement levels.Sulfate resistance has shown promising results in some MSWI bottom ash mixtures. Cheng and colleagues examined MSWI bottom ash application against sulfate attack and reported that appropriate bottom ash content could improve resistance under tested conditions [20]. The mechanism is not universal but may involve filler effects, modified hydration products, consumption of calcium hydroxide, and pore refinement when ash is ground and reactive. Excessive bottom ash or soluble sulfate within the ash can reverse this benefit. This means sulfate durability requires both external-attack testing and internal sulfate assessment. A bottom ash with high sulfate content should not be assumed beneficial merely because another source improved sulfate resistance.Carbonation behavior is mixed. Concrete with porous waste aggregate and lower clinker content may carbonate faster because of higher permeability and reduced alkaline reserve. Conversely, carbonation curing of bottom ash or bottom-ash concrete can stabilize ash phases, reduce leaching and densify the surface. Carbonation of MSWI bottom ash before incorporation reduces pH and immobilizes some metals through carbonate formation [17,19]. For reinforced concrete, carbonation depth must be controlled because loss of alkalinity can depassivate steel. For non-reinforced blocks and pavers, carbonation may be beneficial because it improves dimensional stability and leaching performance.Freeze-thaw resistance depends on saturation, pore structure, air-void system and particle soundness. Porous bottom ash particles increase internal water storage, which can be harmful if the particles are critically saturated. Proper air entrainment can improve freeze-thaw durability, but the ash particles themselves must resist breakdown. Plastic aggregate may reduce freeze-thaw damage in some cases by providing deformable inclusions, but poor bonding can create pathways for water. Glass aggregate is relatively non-absorptive, but ASR-related cracking can destroy freeze-thaw resistance if not controlled. Therefore, freeze-thaw qualification should be required for exterior exposure rather than inferred from compressive strength.

Alkali-silica reaction is most important for glass-containing concrete. Waste glass aggregate can be highly reactive, especially in coarse fractions. The mitigation methods are well established: use finely ground glass powder rather than coarse glass aggregate, limit replacement levels, reduce alkali content, incorporate fly ash, slag, silica fume or metakaolin, and verify expansion through mortar-bar or concrete-prism testing [25,26,27,28]. MSWI bottom ash also contains glassy phases and ceramics, so ASR cannot be ignored. Its reactivity depends on source and treatment. If bottom ash contains significant reactive glass, ASR testing is required before structural use.

Leaching durability is distinct from structural durability but equally important. Cementitious matrices immobilize many metals through high pH precipitation, physical encapsulation and sorption onto hydration products. Yet leaching can increase under carbonation, acid exposure or cracking. MSWI fly ash contains higher trace-metal concentrations than bottom ash, so treated fly ash concrete requires robust leaching verification [3,4,44]. Bottom ash concrete generally shows lower risk after aging and washing, but copper, zinc, lead and salts remain relevant [45,46]. End-of-life crushing can expose new surfaces, so leaching tests on monolithic and crushed specimens give complementary information.A practical synthesis of hardened and durability results is as follows. Bottom ash aggregate replacement up to approximately 10–20% often maintains acceptable compressive strength and durability after treatment; 30–50% may be feasible for non-structural or low-strength applications but commonly reduces strength, stiffness and ingress resistance; 100% replacement is possible in experimental or specialized products but requires intensive processing and application-specific validation [1,2,18,50]. Bottom ash as binder replacement can work at about 10–20% when processed and finely ground, but raw ash is inconsistent [18,19]. MSWI fly ash is unsuitable as an untreated binder in reinforced concrete but can be used after washing, stabilization or vitrification in controlled products [3,5,6]. Waste glass powder can improve later-age strength and durability at suitable fineness, while coarse glass aggregate requires ASR control [26,27,29]. Waste plastic aggregate normally reduces strength and modulus, making it more suitable for lightweight, non-structural, impact-tolerant or insulation-oriented products than primary structural members [33,34,39].

Table 1 summarizes recurring hardened and durability-property findings reported across the literature. The values are not universal design constants; they represent typical directional outcomes from reviewed studies and should be interpreted with source-specific testing. The table is included to make the review operational for mixture selection and experimental planning.

Table 1: Typical hardened and durability-property results for concrete incorporating municipal solid waste-derived materials

Waste constituent and role	Common replacement range in reviewed studies	Hardened-property trend	Durability-property trend	Key references
MSWI bottom ash as fine/coarse aggregate	10–50% by volume, with best structural results usually at low to moderate replacement	Density and modulus decrease; compressive strength acceptable at low replacement but declines as porous ash content increases	Absorption and sorptivity often increase; washing, aging and carbonation reduce chloride, sulfate and leaching risk	[1], [2], [17], [18], [19], [50]
Processed MSWI bottom ash as binder/filler	5–20% by binder mass in optimized mixes	Filler and limited pozzolanic effects can maintain strength; raw ash gives variable hydration	Moderate processed ash can meet chloride and sulfate indicators; untreated ash may increase permeability	[18], [19], [20], [23]
MSWI fly ash as cementitious component	Usually low replacement after treatment; untreated use not recommended for reinforced concrete	Untreated ash may retard hydration; treated ash can act as filler or secondary binder	High chloride, sulfate and metal content create corrosion and leaching risk unless washed or stabilized	[3], [4], [5], [6]
Waste glass as aggregate or powder	Glass sand/aggregate often 10–30%; glass powder commonly 10–20% cement replacement	Coarse glass can reduce bond; fine glass powder can improve later-age strength through pozzolanic reaction	ASR risk is high for coarse glass; fine powder and SCMs reduce expansion and permeability	[25], [26], [27], [28], [29], [30]
Waste plastic as aggregate or fiber	Plastic aggregate commonly 5–20%; fibers at low volume fractions	Compressive strength, tensile strength and modulus usually decrease; density decreases; fibers may improve toughness	Higher interfacial porosity can increase ingress; low absorption and deformability may help selected freeze-thaw or impact cases	[32], [33], [34], [35], [38], [39], [42]

7. ENVIRONMENTAL PERFORMANCE AND SUSTAINABILITY

The sustainability claim for municipal solid waste concrete must be tested rather than assumed. Benefits include reduced landfill disposal, reduced extraction of natural aggregate, potential reduction in clinker consumption and lower transport burden where waste-treatment and concrete-production facilities are geographically close. Incineration bottom ash reuse also recovers value from a residue that would otherwise require disposal [14,16,18]. Yet processing consumes energy and water, and washing creates secondary effluent. If treatment is intensive, the environmental savings may shrink. A credible assessment must include life-cycle inventory, avoided disposal, avoided virgin materials, transport distances, treatment energy, leachate management and service-life effects.

Environmental risk is controlled by leaching and long-term stability. MSWI bottom ash and fly ash may contain heavy metals and soluble salts. If these constituents leach from concrete during service or after demolition, the reuse route may shift contamination from landfill to the built environment. The integrated leaching framework proposed by Kosson and co-workers is relevant because it recognizes pH dependence, liquid-solid ratio, mass transfer, monolithic diffusion and field exposure [44]. Concrete products should be evaluated as monolithic materials during service and as granular recycled material at end of life. A product that passes monolithic leaching may fail granular leaching after crushing. Carbonation is environmentally relevant in two ways. First, carbonation curing can sequester small amounts of carbon dioxide and stabilize ash. Second, natural carbonation during service reduces alkalinity and can change metal mobility. Some metals become less mobile after carbonation because carbonate phases precipitate, while others may become more mobile under lower pH. Therefore, accelerated carbonation is not automatically beneficial; its effect must be measured for the specific ash and matrix [17,45,46].

From a circular-economy perspective, MSWI bottom ash has the strongest case when used in local, controlled, non-prestressed concrete products such as blocks, pavers, kerbs, masonry units, road base concrete, lean concrete and selected precast elements. These products permit factory quality control and easier environmental certification. Structural cast-in-place reinforced concrete is possible but demands stricter chloride, sulfate, ASR, strength, modulus and leaching controls. MSWI fly ash has a narrower window because of its contaminant load. Waste glass powder has a strong sustainability case when it replaces cement fraction and mitigates ASR. Waste plastics have a weaker structural case but may be useful where lightweight behavior, waste diversion and non-structural performance are the main objectives.

8. MICROSTRUCTURE AND MECHANISMS

The microstructural behavior of municipal waste concrete is controlled by three zones: the waste particle, the cement pastes and the interfacial transition zone. In bottom ash concrete, the particle is porous, irregular and mineralogically heterogeneous. Some particles are ceramic or glassy and hard; others are friable, metallic or partially burned. The interfacial transition zone may be rough and mechanically interlocked, but it can also be porous because the particle absorbs water and disrupts local packing. Processing improves the interface by removing weak fines, reducing salts and stabilizing reactive metals [17,21,22].

When bottom ash is ground into a fine powder, its role changes from aggregate to binder component. The fine particles fill voids between cement grains and may react slowly with calcium hydroxide. Chemical activation can enhance this behavior by dissolving aluminosilicate phases and forming additional binding gels [23]. Yet the ash is not a uniform pozzolan. Its reactivity varies with glass content, calcium content, fineness and prior weathering. This explains why some studies report strength improvement at low replacement levels while others report reductions.Fly ash from MSWI interacts with hydration through soluble salts and trace metals. Chlorides can accelerate aluminate reactions and influence ettringite or Friedel’s salt formation. Heavy metals such as zinc and lead can retard hydration by forming surface precipitates on cement grains. Free lime can increase early alkalinity and heat. Washing changes this chemistry by removing soluble ions, but it may also remove reactive alkalis and alter particle surfaces [3,4,5]. Successful use of fly ash therefore depends on transforming a hazardous fine residue into a predictable mineral addition.

Glass powder contributes through pozzolanic reaction when sufficiently fine. Its amorphous silica dissolves in alkaline pore solution and reacts with calcium hydroxide to form additional calcium-silicate-hydrate. Coarse glass, by contrast, behaves mainly as aggregate and can create ASR gel at the particle boundary [26,27]. Plastic particles are mostly inert and hydrophobic. Their main microstructural effect is physical: they create weak interfaces, reduce stiffness and may increase entrapped air. Surface roughening, chemical treatment or coating can improve bonding, but the elastic mismatch remains.

The microstructure explains why “waste replacement percentage” is an inadequate predictor. Two concretes with 20% municipal waste can behave differently if one contains aged, washed, graded bottom ash as sand and the other contains untreated fly ash as binder. Performance-based design must therefore classify the waste by function: aggregate, filler, binder, fiber or lightweight inclusion. Each function has a different mechanism and different failure mode.

9. APPLICATION POTENTIAL

The safest near-term applications for municipal solid waste concrete are controlled precast and non-structural products. Paving blocks, masonry blocks, kerb-stones, partition panels and lean concrete can tolerate moderate variability and permit production-plant quality control. In these applications, bottom ash can replace part of the fine aggregate or binder, and waste glass powder can replace part of cement. Strength classes can be adjusted through mix design, and leaching can be tested on finished products [16,18].

Structural reinforced concrete is more demanding. Chloride content must be low, steel corrosion risk must be controlled, modulus and creep must be known, and durability must match exposure class. Bottom ash may be feasible at low to moderate replacement levels after treatment, especially in exposure conditions without severe chloride or freeze-thaw loading. Fly ash from MSWI should not be used in reinforced concrete without strong evidence of chloride reduction, heavy-metal immobilization and hydration compatibility [3,5,6]. Plastic aggregate should be restricted unless structural design accounts for reduced stiffness and strength.

Road construction and base materials are outside conventional structural concrete but remain important. MSWI bottom ash has been widely examined as road sub-base, embankment and pavement material because its granular nature suits these applications [8,10,49]. Concrete-related road applications include roller-compacted concrete, lean concrete and cement-treated base. Environmental controls are still necessary because road exposure involves rainfall infiltration and long-term contact with soil and groundwater.

High-performance and ultra-high-performance concrete with municipal waste is an emerging field, but the material constraints are severe. UHPC relies on dense packing, low water-binder ratio, high-quality powders and strong interfaces. Raw bottom ash is usually too porous and variable for high replacement levels. Finely processed ash or glass powder may function as filler or partial binder, but qualification must be rigorous. The highest-value application may not be replacing the maximum amount of waste, but using a controlled small fraction without compromising durability.

10. CONCLUSION

Concrete incorporating municipal solid waste is technically feasible, but its success depends on rigorous characterization and controlled processing. MSWI bottom ash is the most promising MSW-derived constituent because it is granular, available in large quantities and capable of replacing part of the aggregate or binder after aging, washing, metal removal, grading and sometimes carbonation. At low to moderate replacement levels, particularly around 10–20%, processed bottom ash can produce concrete with acceptable compressive strength, tensile performance and durability. Higher replacement levels are possible but usually shift the product toward non-structural or specialized applications unless intensive mix optimization is used.

MSWI fly ash is more difficult because it concentrates chlorides, sulfates, soluble salts and heavy metals. It should not be treated as equivalent to conventional coal fly ash. Its use in concrete requires washing, stabilization, vitrification, carbonation or other treatment, followed by hydration, durability and leaching verification. Waste glass can be beneficial when finely ground as a pozzolanic powder but risky as coarse aggregate because of alkali-silica reaction. Waste plastics reduce density and may improve selected functional properties, but they generally reduce strength, stiffness and bond, making them more suitable for non-structural lightweight products than primary structural concrete.

The hardened and durability results from the literature show a consistent pattern: municipal waste materials can work when their deleterious phases are removed or immobilized and when replacement levels are aligned with material function. Strength alone is insufficient. Water absorption, chloride ingress, sulfate resistance, carbonation, freeze-thaw resistance, ASR, shrinkage, modulus and leaching must be evaluated together. The most defensible route is performance-based qualification of treated municipal waste as an engineered secondary raw material. With this approach, municipal solid waste concrete can contribute to resource conservation and landfill reduction without compromising structural safety or environmental protection.

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