Review of the Effect Of Induction Furnace Slag, Ternary Plc, RHA and WGP Blended Cement on The Mechanical and Microstructural Properties of Concrete

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ABSTRACT: *The growing demand for environmentally sustainable construction materials has become increasingly critical due to the significant environmental impacts associated with conventional concrete production, particularly carbon emissions from cement manufacturing and the depletion of natural aggregate resources. Consequently, industrial and agricultural waste materials have gained attention as alternative aggregates and supplementary cementitious materials. This review critically evaluates the mechanical and microstructural performance of concrete incorporating induction furnace slag (IFS) as a replacement for natural aggregates, together with a ternary blended binder consisting of Portland limestone cement (PLC), rice husk ash (RHA), and waste glass powder (WGP). This new composite aim to improve concrete performance while reducing its environmental footprint. Existing studies indicate that IFS exhibits favorable engineering properties, including high hardness and a rough surface texture, which enhance interfacial bonding and contribute to improved compressive, tensile, and flexural strengths when used at appropriate replacement levels. The incorporation of RHA and WGP contributes significant pozzolanic activity due to their high amorphous silica content, promoting secondary hydration reactions, increasing calcium silicate hydrate (C-S-H) formation, reducing calcium hydroxide, and refining the pore structure. Microstructural analyses using techniques such as SEM, XRD, and FTIR consistently reveal a denser cement matrix and stronger interfacial transition zones. Despite these benefits, challenges such as material variability, potential contaminants in slag, and optimization of mix proportions remain critical considerations. Overall, this review highlights the potential of combining IFS aggregates with PLC, RHA, and WGP blended cement to produce high-performance, eco-friendly concrete while reducing dependence on conventional construction materials.*

Keywords: *Induction furnace slag, rice husk ash, waste glass powder, ternary blended cement, structural performance.*

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I. INTRODUCTION

Concrete continues to be the most extensively used construction material worldwide due to its adaptability, structural efficiency, and economic viability. However, rapid urbanization and population growth have significantly increased the demand for cement and natural aggregates, thereby intensifying environmental concerns associated with their production. In particular, cement manufacturing is highly energy-intensive and contributes substantially to global greenhouse gas emissions, prompting the need for more sustainable alternatives (Habert et al., 2020).

Globally, the cement industry is responsible for a considerable proportion of anthropogenic carbon dioxide emissions, largely due to limestone calcination and fossil fuel combustion during clinker production (Andrew, 2019). One effective strategy to mitigate these emissions is the reduction of clinker content through the adoption of blended cement systems. PLC has emerged as a viable option, as it incorporates finely ground limestone to partially replace clinker, thereby lowering carbon emissions while maintaining comparable performance. Additionally, limestone particles improve particle packing and act as nucleation sites that enhance early hydration reactions (Bentz et al., 2019). Beyond clinker reduction, the use of supplementary cementitious materials (SCMs) derived from waste streams provides another pathway towards sustainable concrete production. RHA, an agricultural by-product obtained from controlled combustion of rice husks, has been widely studied due to its high silica content and strong pozzolanic properties. When incorporated into cementitious systems, RHA reacts with calcium hydroxide to form additional C-S-H gel, resulting in improved strength, reduced permeability, and enhanced durability (Zhang et al., 2022).

Similarly, WGP produced from finely ground discarded glass has demonstrated promising performance as a pozzolanic material. Its utilization not only enhances long-term mechanical properties through secondary hydration reactions but also contributes to waste management and promotes circular economy practices in construction (Rashad, 2023). The combined use of multiple SCMs in ternary systems has been reported to produce synergistic effects, improving hydration kinetics, packing density, and overall microstructural development (Shi et al., 2020).

In addition to cement-related concerns, the excessive extraction of natural aggregates has led to environmental degradation, including riverbed erosion and ecosystem disruption (Tam et al., 2018). Consequently, alternative aggregates derived from industrial by-products are being increasingly explored. IFS, a waste material generated during steel production, possesses desirable physical characteristics such as high density and angularity, making it a suitable candidate for aggregate replacement in concrete (Pundhir & Prakash, 2021).

When these components are utilized in the right amounts, they not only reduce environmental pollution but also improve the mechanical and durability aspects of concrete (Prusty et al., 2021). However, to fully realize their potential, they must undergo a thorough physical, chemical, and mineralogical analysis. This ensures the identification of reactive ingredients, hydration behavior, and PLC compatibility.

Previous studies have shown that slag aggregates can improve mechanical performance due to enhanced interlocking and stronger bonding at the aggregate-paste interface. However, their influence on hydration behavior and microstructural features, particularly within the interfacial transition zone, requires further investigation (Singh et al., 2022). Plates 1, 2, and 3 below show Rice husk and RHA, IFS, and WGP, respectively.

Plate 1: Rice Husk & RHA (Mitikie et al., 2025) **Plate 2: Induction Furnace Slags (Uzunömeroğlu & İlker 2023)**

Plate 3: Waste Glass Powder (Çelik et al., 2023)

Given the increasing emphasis on low-carbon construction materials, a comprehensive evaluation of such systems is essential. This review, therefore, aims to synthesize current research on the mechanical and microstructural behavior of concrete incorporating IFS aggregates and ternary blended cement, while also identifying existing knowledge gaps and future research directions.

II. MATERIALS AND METHODS

The approach adopted for this review is to obtain all the scholarly works on concrete containing ternary blends of PLC, RHA, and WGP, incorporating IFS as coarse aggregate, that are available on the internet.

The development of sustainable concrete incorporating industrial and agricultural by-products requires a careful selection and characterization of its constituent materials. In concrete systems utilizing IFS as aggregate and a ternary blended binder consisting of PLC, RHA, and WGP, the properties of each component significantly influence both mechanical performance and microstructural evolution. The primary materials include cementitious binders, SCMs, aggregates, water, and, where necessary, chemical admixtures.

2.1 PORTLAND LIMESTONE CEMENT (PLC)

PLC is a blended hydraulic binder produced through the intergrinding of clinker, gypsum, and a controlled proportion of finely ground limestone. The partial substitution of clinker with limestone has gained increasing attention as an effective approach to reducing the environmental footprint of cement production. By lowering clinker content, PLC contributes to reduced carbon dioxide emissions and energy consumption while maintaining comparable mechanical properties to conventional Portland cement (Li et al., 2023).

The fine limestone particles primarily function as micro-fillers, improving particle packing within the cement matrix. In addition, they provide nucleation sites that accelerate early hydration reactions, leading to improved early-age strength development. PLC is standardized under ASTM C595/C595M as Type IL cement, which specifies allowable limestone content and ensures compliance with strength and durability requirements for structural applications (ASTM, 2025).

Experimental studies have demonstrated that PLC-based concrete can achieve mechanical performance comparable to ordinary Portland cement systems. Zhang et al. (2023) reported similar compressive strength with enhanced resistance to chloride penetration, while Akerele et al. (2025) confirmed its suitability for infrastructure applications such as pavements and bridge decks.

From a microstructural perspective, the presence of limestone promotes the formation of carboaluminate phases through reactions with aluminate compounds, contributing to improved matrix stability and long-term hydration (Tang et al., 2023). When combined with highly reactive SCMs such as RHA and WGP, PLC enhances the formation of calcium silicate hydrate (C-S-H), resulting in reduced porosity and improved durability. Furthermore, PLC contributes to a stronger interfacial transition zone (ITZ), particularly in systems incorporating alternative aggregates such as IFS, thereby improving overall concrete performance (Singh et al., 2023).

2.2 SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMs)

SCMs are finely divided materials used with Portland cement to enhance the performance and sustainability of concrete. These materials exhibit hydraulic or pozzolanic properties and react with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C-S-H), which improves the strength and durability of concrete (Juenger, et al., 2019). The use of SCMs is widely encouraged in modern concrete technology because they reduce Portland cement consumption and consequently decrease the CO_2 emissions associated with cement production (Scrivener, et al., 2018).

SCMs may originate from industrial by-products, agricultural wastes, or natural pozzolans. Common examples include fly ash, ground granulated blast furnace slag (GGBFS), silica fume, RHA, metakaolin, and WGP (Thomas, 2013). Fly ash, produced from coal combustion in power plants, improves workability and long-term strength development in concrete. GGBFS, a by-product of the iron and steel industry, enhances sulfate resistance and reduces permeability in cementitious systems (Provis & van Deventer, 2014).

Silica fume is an ultrafine material generated during silicon alloy production and significantly improves the microstructure and strength of concrete due to its high silica content and filler effect (Mehta & Monteiro, 2014). Agricultural waste materials such as RHA are also widely used because of their high amorphous silica content and strong pozzolanic reactivity (Habeeb & Mahmud, 2010). In addition, finely ground WGP has shown promising pozzolanic behavior and contributes to improved mechanical and durability properties of blended cement systems (Du & Tan, 2017).

Therefore, the incorporation of SCMs plays a vital role in producing durable and environmentally sustainable concrete while promoting the utilization of industrial and agricultural waste materials (Juenger et al., 2019).

2.2.1. RICE HUSK ASH (RHA)

RHA is an agricultural by-product of burning husk under controlled temperatures of below 800^0C. RHA improves concrete's durability, strength, and thermal insulation properties due to its fine particle size and high silica content (Mehta, 2018). The increasing demand for environmentally friendly construction materials has driven research into the use of RHA as a partial replacement for cement in concrete. According to (Amran et al., 2021), the utilization of RHA not only enhances concrete performance but also reduces environmental pollution associated with agricultural waste disposal.

RHA is characterized by a high concentration of amorphous silica, typically ranging from 85-90% as reported by (Panda & Prusty 2015). This high silica content is the primary factor responsible for its strong pozzolanic behavior. Several researchers, including (Mahmud et al. 2010), (Chindaprasirt et al. 2008), have documented the high pozzolanic activity of RHA, attributing it to the presence of amorphous silica, fineness, and elevated specific surface area. The particle size of RHA plays a significant role in determining its reactivity. (Fapohunda et al. 2017) noted that maximum reactivity is achieved when particle size is reduced to below 8 micrometers. Mineralogical analysis through X-ray diffraction has identified phases such as quartz, cristobalite, and anorthite within RHA, as reported by (Farooque et al. 2009), which collectively support its overall amorphous structure as emphasized by (Bouzoubaa & Fournier 2001). The reactivity of RHA is further confirmed by its ability to cause a reduction in conductivity when mixed with saturated lime, indicating its strong affinity for calcium hydroxide.

(Xu et al., 2016) Provided more evidence to support this discovery, suggesting that RHA can be used as 10% to 20% replacement for cement in concrete without negatively impacting performance. This result can be attributed to RHA's substantial pozzolanic features. Furthermore, (Bheel et al., 2020) discovered that concrete containing rice husk ash (RHA) had a higher compressive strength than conventional concrete, implying that RHA improves concrete durability.

The physical characteristics of RHA are strongly influenced by its production process, particularly combustion temperature and duration. Scanning electron microscopy studies by (Farooque et al. 2009) reveal that RHA particles possess a highly porous and fibrous structure with a honeycombed appearance, contributing to a high specific surface area. This microstructural configuration enhances the reactivity and filling ability of RHA when incorporated into concrete. In terms of its effect on concrete density, RHA-blended concrete generally exhibits higher density compared to conventional concrete, with typical values ranging between 2200 and 2550 kilograms per cubic meter, as noted by (Fapohunda et al. 2017). However, an increase in RHA replacement levels tends to result in a slight reduction in overall density due to the lighter nature of the ash. The incorporation of RHA also improves the mechanical performance of concrete. (Alex et al. 2016) demonstrated that concrete containing RHA achieves enhanced strength, primarily due to improved hydration of calcium silicate phases when compared to OPC concrete. The chemical and physical properties of RHA from different authors are presented in Tables 1 & 2.

Table 1: Chemical Composition of Rich Husk Ash Reported by Different Authors

References	Chemical Constituents (Weight %)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_2	Na_2O	K_2O	Others	LOI
(Umasabo r& Okovido 2018)	87.22	0.70	1.68	2.12	1.18	0.04	0.20	1.12	0.46	1.06
(Hesami et al., 2024)	86.02	0.36	0.16	1.12	0.39	-	1.15	-	-	-
(Al-Shemasneh et al., 2015)	87.30	0.32	0.52	-	0.77	1.32	0.19	3.58	-	9.31
(Abdulwahab et al., 2021)	83.62	1.43	0.78	1.24	0.09	-	0.04	0.08	-	-
(Olubajo et al., 2020)	81.28	2.42	0.71	0.75	1.09	0.23	0.18	4.02	-	-
(Balapour et al., 2017)	83.74	0.29	0.67	0.74	0.86	0.87	0.091	2.84	0.37	8.39
(Raheem et al 2021)	82.14	1.34	1.27	1.21	1.96	0.17	0.14	2.09	6.44	-
(Huang et al., 2017)	91.56	0.19	0.17	1.07	0.65	0.47	0.16	3.76	-	-

Table 2: Physical Properties of Rich Husk Ash Reported by Different Authors

References	Specific gravity	Blaine Fineness (m^2/g)	Average particle size (µm)	Specific surface area (m^3/kg)	Specific surface (BET) (m^2/g)
Habeeb et al., 2010	2.11	-	11.50	-	30.40
Ganesan et al., 2008	2.06	-	-	-	36.47
Chao-Lung et al., 2011	2.06	-	-	-	-
(Ordonez et al., 2024)	-		7.8-72.8	1.6-36.5	

2.2.2 WASTE GLASS POWDER (WGP)

WGP is a finely ground material produced from discarded glass, such as bottles, window glass, and other glass products. It is increasingly used in construction materials, particularly in cement and concrete, due to its high silica content and pozzolanic reactivity. The reuse of waste glass in powder form provides an environmentally sustainable approach to reducing landfill waste and lowering the consumption of natural resources in concrete production (Zhang et al., 2022).

Incorporation of industrial and municipal waste materials in construction has gained considerable attention as a sustainable approach to reduce environmental impacts associated with conventional building materials. Among these alternatives, WGP has attracted increasing interest as an SCM in concrete production. The utilization of WGP not only helps mitigate the environmental burden of glass waste disposal but also contributes to reducing cement consumption and the associated carbon emissions. When finely ground, waste glass demonstrates significant pozzolanic potential, making it suitable for partial replacement of cement in cementitious systems (Rashad, 2023).

Waste glass is primarily composed of silica (SiO_2), which forms the dominant constituent of its chemical structure. In addition to silica, it contains other oxides such as sodium oxide (Na_2O), calcium oxide (CaO), and aluminum oxide (Al_2O_3). This oxide composition is particularly important because finely ground glass particles become chemically active in cementitious environments. When incorporated into concrete, the reactive silica in WGP can interact with calcium hydroxide [$Ca(OH)_2$] produced during cement hydration. This pozzolanic reaction results in the formation of additional calcium silicate hydrate (C-S-H) gel, which is the primary phase responsible for the strength and durability of hardened cement paste. Consequently, the presence of WGP can improve the mechanical and durability characteristics of concrete while also enhancing microstructural densification (Du & Tan, 2014).

WGP's smooth particles have a high specific surface area, which helps with packing and filling effects. It is primarily composed of amorphous silica with traces of crystalline quartz in terms of mineralogy. As long as the fineness is adequate to inhibit Alkali-Silica Reactivity (ASR) expansion, several studies have demonstrated that substituting 10-20% WGP for cement increases mechanical strength and decreases permeability (Patel et al., 2018).

The performance of WGP as a SCM is strongly influenced by its physical characteristics, particularly particle size and fineness. Studies have indicated that when glass powder is ground to a particle size typically below 75 µm, its pozzolanic activity increases significantly. The enhanced reactivity is largely attributed to the high surface area of the fine particles, which facilitates improved interaction with hydration products in cement-based systems. Furthermore, the silica present in waste glass generally exists in an amorphous form, which is more chemically reactive than crystalline silica. This amorphous structure enables effective participation in pozzolanic reactions, thereby improving the strength development, durability, and microstructural integrity of concrete containing WGP (Wang et al., 2023).

Table 3: Chemical Composition of Waste Glass Powder Reported by Different Authors

References	Chemical Constituents (Weight %)									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Others	LOI
(Subramani&Sankar Ram 2015)	72.5	0.4	0.2	9.7	3.3	-	13.7	0.1	-	0.36
(Lu et al., 2017)	73.5	0.73	0.38	10.48	1.25	-	12.74	0.69	0.087	-
(Roy et al., 2016)	78.0	0.50	2.0	7.5	1.5	-	-	-	0.80	-
(Zhu et al., 2023)	67.79	3.51	0.53	11.37	0.62	0.80	13.89	0.87	0.15	-
(Aliabdo, 2016)	71.40	2.54	0.37	11.2	1.60	0.16	12.25	0.36	0.04	0.82
(Jena, &Paikaray 2018)	72.5	0.4	0.2	9.7	3.3	-	13.7	0.1	-	-

Table 4: Physical Properties of Waste Glass powder Reported by Different Authors

Particle Sizes	Specific Surface area (cm^2/g)	Specific Gravity	Water Absorption (%)	Fineness Modulus or passing (%)	References
<75mm	-	2.55	1.60	2.65	(Islam et al., 2016)
<80µm	8000	-	-	-	Chaïd et al., (2015)
≤ 38µm	3100	3.10	-	98	Ahmad et al., (2022)
150 µm	-	2.60	-	99.5	(Abdullah, 2016)
5-150µm	-	2.41	0.09	2.2	(Tahwia et al., 2023)

2.3. AGGREGATES

Aggregates, which are granular materials primarily derived from natural rock (crushed stone or natural gravels) and sands, typically make up 70–80% of the volume of concrete and have a significant impact on its properties. To achieve a good concrete quality, aggregates must be strong, hard, free of unwanted impurities, and chemically stable (Batra, 2018).

2.3.1 COARSE AGGREGATE (INDUCTION FURNACE SLAG)

IFS is a by-product of steel manufacturing generated during melting processes in induction furnaces. Its utilization as an alternative aggregate supports sustainable construction by reducing dependence on natural resources and minimizing industrial waste disposal. Chemically, IFS is composed of oxides such as calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), which influence its engineering properties (Chandru et al., 2021).

Physically, IFS particles are typically angular and rough-textured, which enhances mechanical interlocking and bonding with the cement matrix. The material also exhibits relatively high density compared to conventional aggregates, contributing to increased unit weight in concrete. However, its porous nature can result in higher water absorption, necessitating adjustments in mix design to maintain workability and performance (Miah et al., 2021). Although there is a lot of variation based on feedstock and furnace conditions, its composition usually consists of oxides of calcium, iron, silicon, and magnesium (Das et al., 2021).

Studies have shown that partial replacement of natural aggregates with IFS can improve compressive strength and density. (Baalamurugan et al. 2019) reported enhanced strength and density at moderate replacement levels, while (Uzunömeroğlu & İlker, 2023) observed increased unit weight and improved mechanical performance in mixes containing IFS. Optimal replacement levels are generally reported within the range of 20–50%, beyond which strength reductions may occur due to increased porosity and weaker internal structure.

Additionally, IFS has been successfully applied in specialized concrete, such as pervious concrete, where its grading and porosity contribute to adequate permeability while maintaining sufficient compressive strength (Sherfenaz et al., 2025). IFS presents a viable and sustainable alternative aggregate when used within appropriate limits.

Table 5: Comparison of Typical Properties of Induction Furnace Slag (IFS) and Natural Aggregates (NA).

Properties	Induction Furnace Slag (IFS)	Natural Aggregate (NA)	Relevant Standard Requirements	References
Specific Gravity	3.24	2.6-2.75	(ASTM C127)	(Miah et al., 2021; Mindess et al., 2003)
Water Absorption (%)	0.1-1.5	0.5-2.0	(ASTM C127)	(Barbhuiya et al. 2014; Miah et al.,2021)
Abrasion value (%)	<20	≤30	<30 (ASTM C131)	(Miah et al., 2021)
Particle shape/Texture	Angular & Rough	Rounded & Smooth	Angularity preferred for interlock (ASTM D4791)	(Mindess et al., 2003)
Bulk Density (Kg/m^3)	1462	1500-1800	Dependent on concrete mix design (ASTM C29)	(Barbhuiya et al. (2014; Ahmad &Rahman 2018)
Crushing value	10-25	15-30	<30 (BS 812-110)	(Barbhuiya et al. (2014)
Flakiness Index (%)	Very Low (<5)	Typically higher (12)	<15 (IS Code limit)	(Barbhuiya et al. (2014)

Table 6: Chemical Composition of Induction Furnace Slag Aggregates Reported by Different Authors

Chemical Composition (%)	(Roy et al., 2023)	(Ahmad &Rahman 2018)	(Mark et al., 2021)	(Birgonda et al., 2024)
SiO_2	40.01	40.59	44.57	43.4
Al_2O_3	7.85	13.54	11.10	9.8
Fe_2O_3	23.29	20.05	22.97	25.8
CaO	12.80	11.68	-	10.58
MnO	9.73	7.12	9.65	8.56
Na_2O	-	0.34	0.44	-
MgO	-	1.4	1.62	-
LOI	-	4.8	9.97	-

2.3.2 FINE AGGREGATE

Fine aggregates play an important part in the composition and performance of concrete, acting as a filler material to increase the mixture's overall strength and durability. Natural sand has long been the preferred fine aggregate due to its availability and desirable features, such as particle shape and gradation (Patel & Gupta, 2018). The fine aggregate used was locally sourced sand that met the IS 383 zone II standards, and it was carefully sieved using a 4.75 mm screen to ensure it was free of silt and organic debris. The specific gravity of the sand, which is 2.65, was used (Premkumar et al., 2024).

2.4 WATER

Water is a fundamental component in concrete production, as it initiates the hydration process of cement and facilitates the formation of a cohesive matrix that binds aggregates together. The interaction between water and cement leads to the formation of hydration products responsible for strength development and durability (Scrivener et al., 2018).

The water-cement ratio is a critical parameter influencing concrete properties. Lower ratios generally produce higher strength and durability due to reduced porosity, while excessive water increases pore volume and weakens the cement matrix (Zhang et al., 2022).

In addition to quantity, water quality is essential. Mixing water should be free from harmful impurities that may interfere with hydration or compromise durability (Mindess et al., 2003). Standards such as ASTM C1602/C1602M specify acceptable limits for water quality to ensure compatibility with cementitious materials.

Water also plays a key role in workability and curing. Adequate water content ensures proper mixing and placement, while proper curing maintains moisture for continued hydration, leading to improved strength and reduced cracking (Neville & Brooks, 2024).

III. MECHANICAL PROPERTIES OF CONCRETE WITH IFS AND TERNARY PLC, RHA, AND WGP BLENDED CEMENT

The mechanical performance of concrete incorporating induction furnace slag (IFS) as aggregate and ternary blended cement systems, such as PLC, RHA, and WGP, has attracted increasing research interest due to its potential to achieve sustainability without compromising structural integrity. Key properties commonly evaluated include compressive strength, flexural strength, and splitting tensile strength.

3.1 COMPRESSIVE STRENGTH

Compressive strength remains the primary indicator for assessing the structural performance of concrete. Studies on ternary blended systems have demonstrated that the combined use of PLC, RHA, and WGP can significantly enhance strength development due to both physical and chemical mechanisms. RHA contributes to long-term strength through its pozzolanic reaction, whereby amorphous silica reacts with calcium hydroxide released during cement hydration to produce additional calcium silicate hydrate (C-S-H), resulting in a denser and stronger cement matrix (Torres-Ortega et al., 2025). WGP, owing to its fine particle size and high silica content, improves particle packing, acts as a micro-filler, and also exhibits pozzolanic activity at later ages, thereby enhancing compressive strength and refining the pore structure of concrete (Du & Tan, 2014).

The incorporation of IFS as aggregate has also been shown to positively influence compressive strength when used at appropriate replacement levels. (Uzunömeroğlu & İlker 2023) reported that concrete containing IFS exhibited higher compressive strength compared to conventional mixes, with improvements attributed to enhanced interfacial bonding and the angular nature of slag particles. Similarly, (Baalamurugan et al. 2019) observed that partial replacement of natural aggregates with IFS resulted in increased density and improved compressive strength.

The addition of RHA further enhances compressive strength at optimal replacement levels, typically within 5-10% (Li et al., 2024). This improvement is primarily due to microstructural densification and refinement of pore structure. (Siddika et al. 2018) reported that concrete with approximately 10% RHA achieved strength comparable to control mixes, while other studies have shown improved performance at similar replacement levels due to enhanced hydration. (Akinpelu et al., 2024) reported that varying proportions of agricultural ashes were incorporated into the cementitious system to evaluate their influence on the compressive strength of concrete. The study revealed that increasing the content of RHA improved compressive strength up to an optimum level. The mixture containing approximately 8.5% RHA, 10% guinea corn husk ash, and 82.5% cement achieved the best performance, attaining a compressive strength of about 31.34MPa at 56 days of curing. This result indicates that the incorporation of controlled quantities of agricultural ashes can enhance the mechanical performance of concrete compared with mixes produced without such additives.

Several studies have investigated the influence of waste glass incorporation on the compressive strength of concrete. Experimental findings reported by (Olofinnade. et al. 2017) indicated that concrete mixtures containing approximately 20% waste glass achieved the highest improvement in compressive strength across different curing periods, suggesting that moderate glass replacement can enhance the mechanical performance of concrete. Similarly, (Kumar, et al. 2017) observed that incorporating an optimum proportion of about 20% waste glass particles in the concrete mix resulted in higher compressive strength compared with conventional concrete, which was attributed to improved particle packing and potential pozzolanic reactivity of finely ground glass.

Earlier experimental work by (Chikhalikar, et al. 2012) also demonstrated that replacing conventional materials with waste glass within the range of 10-30% produced notable strength gains, with increases of approximately 4%, 16%, and 9% reported for different replacement levels. These improvements were associated with the filler effect of finely ground glass particles, which enhances the density of the cement matrix. In addition to mechanical benefits, the study by (Islam, et al. 2017) highlighted that a replacement level of around 20% waste glass represents a practical balance between performance enhancement, economic considerations, and environmental sustainability. The use of waste glass at this level not only improves compressive strength but also contributes to waste management and reduction in the consumption of natural raw materials.

(Alizadeh et al., 2018) largely replaced IFS with coarse particles in normally-vibrated concrete. It was found that the strength properties of the final concrete were enhanced by partially substituting the coarse aggregate for IFS.

3.2 FLEXURAL STRENGTH

Flexural strength is an important parameter that reflects the resistance of concrete to bending and crack propagation. The incorporation of IFS aggregates has been reported to improve flexural performance due to their rough surface texture and angular shape, which enhance bonding between aggregates and cement paste. (Das et al. 2023) observed that concrete containing IFS exhibited improved resistance to bending stresses and delayed crack initiation.

Similarly, studies involving recycled aggregate concrete have shown that the addition of IFS further enhances flexural strength, particularly at moderate replacement levels. (Araf et al. 2023) reported that optimal performance was achieved at approximately 10% IFS replacement, beyond which the rate of improvement decreased.

The influence of RHA on flexural strength is somewhat variable. While moderate replacement levels can improve performance through pore refinement and matrix densification, higher replacement levels may reduce strength due to insufficient cementitious material. (Siddika et al. 2018) reported that optimal performance is typically achieved within a limited replacement range, beyond which flexural strength declines. Maximum flexure strength of incorporating RHA is achieved for 5% RHA replacement, but at 10% RHA replacement, strength decreases slightly from control mix strength (Singh et al., 2016)

WGP has also been shown to enhance flexural strength when used in appropriate quantities. (Zeybek et al. 2022) reported improved flexural performance at replacement levels between 10% and 20%, while higher levels resulted in reduced strength due to weaker bonding within the matrix. Similar findings were reported by (Chikhalikar et al. 2012), who attributed the improvement to the filler effect and improved packing density of fine glass particles.

In general, flexural strength improved in ternary blended systems due to enhanced interfacial bonding and reduced microcracking, provided that material proportions are carefully controlled.

3.3 SPLITTING TENSILE STRENGTH

Splitting tensile strength is a critical parameter for evaluating the cracking resistance and tensile behavior of concrete. The incorporation of IFS as aggregate has been shown to enhance tensile strength due to its high hardness and rough surface characteristics, which improve stress transfer within the concrete matrix. Studies have indicated that optimal performance is achieved at moderate replacement levels, particularly around 50% IFS content (Ahmed & Rahman 2018).

The split tensile strength also tends to increase with increasing percentages of RHA up to 5% mix but slightly decreases after 10% replacement, and is more than control mix, on increasing percentage replacement of cement with RHA 5%, there is a reduction in the tensile strength value therefore 5% RHA replacement is optimum for split tensile strength (Singh et al., 2016). (Ahmad & Rahman 2018) observed that concrete containing IFS exhibited improved tensile performance compared to conventional mixes.

The inclusion of RHA can also influence tensile strength through microstructural refinement. (Varadharajan et al. 2020) reported improvements in tensile strength due to reduced porosity and enhanced hydration. However, excessive RHA content may reduce tensile strength due to incomplete reactions and weaker bonding (Siddika et al., 2018).

WGP has demonstrated beneficial effects on tensile strength at lower replacement levels. (Aliabdo et al. 2016) reported that tensile strength increased at replacement levels up to 10%, after which it declined due to reduced cohesion within the matrix. This trend highlights the importance of maintaining optimal proportions to achieve improved performance. (Diao et al. 2023) also indicated that excessive glass content could reduce tensile performance because of weaker interfacial bonding between the glass particles and cement paste. The splitting tensile strength improved when the replacement level ranged between 10% and 30%, while a reduction in tensile strength was observed when the replacement increased to 40%, indicating that excessive glass content can negatively affect the bonding within the concrete matrix (Chikhalikar et al., 2012).

Overall, the combined use of IFS, RHA, and WGP can enhance tensile properties through improved bonding and microstructural densification, although excessive replacement levels may adversely affect performance.

Table 7: Mechanical Properties of IFS, RHA & WGP

References	Percentage Replacement	Slump Value	Compressive Strength	Flexural Strength	Tensile Strength
(Ahmad & Rahman 2018)	0-100%	No segregation was observed during concrete mix	For up to 50% IFS replacement, compressive strength increased	-	Found to be highest for concrete with 50% IFS, found lower at 100% IFS Concrete.
(Mark et al., 2021)	0-50%	Decreased in slump flow as % replacement increased from 10-50% compared with control mix	Increased as curing ages increased	Increased	Increased
(Saravanan & Sirvaraja, 2016)	10-20%	-	Increased	Increased by 20%	Increased
(Singh, et al., 2016)	5-20%	Decreases with increasing RHA content due to reduced workability of the mix	Optimum RHA content is achieved at 10% RHA replacement, beyond which a reduction in strength occurs.	Strength reaches its peak at 5% RHA replacement and decreases slightly at higher replacement levels.	Strength reaches its peak at 5% RHA replacement and declines further with increases in RHA content
(Jena & Paikaray, 2018)	5-15%	Decreases with increasing WP content due to reduced cement paste and workability	Increases with WG replacement up to 10% due to pozzolanic and filler effects, after which it decreases due to dilution	Follows a similar trend, improving up to 10% replacement and declining beyond	Increases up to 10% WP content and reduces when the replacement exceeds the optimum level
(Herki et al., 2017)	0-60%	Remains largely unaffected by increasing WG content, indicating no significant change in workability	Decreases with increasing WG content in the concrete mix	Decreases with higher WG content, consistent with the reduction in overall mechanical performance	Decreases as the proportion of WG in the concrete increases
Ahmad, et al., 2022	5-30%	Increases with higher WG content due to lower water absorption and improved lubrication within the mix	Strength decreases at early ages but increases with curing up to an optimum of about 20% WG replacement; beyond it declines due to dilution and alkali reactions.	Similar strength increases with curing up to 20% WG content but reduces beyond this level.	Increases with curing up to 20 & WG content

IV. MICROSTRUCTURAL PROPERTIES OF CONCRETE WITH IFS AND TERNARY BLENDED PLC, RHA, AND WGP CEMENT

The microstructural behaviour of concrete incorporating IFS and ternary blended cement comprising PLC, RHA, and WGP is strongly influenced by hydration processes, pozzolanic reactions, and interfacial bonding within the matrix.

The microstructural characteristics of IFS differ from conventional aggregates due to its porous and angular nature. (Siddique & Kaur2022) reported that IFS particles often contain micro-voids and irregular textures, which can weaken the ITZ. However, (Yüksel et al. 2023) found that when used in moderate proportions, IFS improves particle packing and contributes to a more stable internal structure. Their study revealed that excessive IFS content increases pore volume and leads to discontinuities within the matrix.

Recent studies indicate that RHA significantly enhances the internal structure of concrete due to its high amorphous silica content. (Nduka et al. 2022) reported that RHA participates actively in pozzolanic reactions, consuming calcium hydroxide and forming additional calcium silicate hydrate (C-S-H), which leads to a denser microstructure. Similarly, (Zareei et al. 2022) observed through Scanning Electron Microscopy(SEM) analysis that concrete containing optimum RHA exhibited fewer voids and a more homogeneous matrix, while excessive RHA resulted in unreacted particles and micro-cracking due to insufficient calcium hydroxide for complete reaction.

WGP contributes to microstructural refinement through both physical and chemical mechanisms. (Aliabdo et al., 2016) noted that finely ground glass particles act as micro-fillers, occupying void spaces between cement grains and improving packing density. In addition, (Islam et al. 2024) demonstrated that the silica-rich composition of WGP enhances secondary hydration, resulting in increased C-S-H formation and reduced porosity. Their findings further showed that WGP reduces the connectivity of capillary pores, thereby improving durability characteristics.

The combined use of PLC, RHA, and WGP produces a synergistic improvement in concrete microstructure. (Golewski, 2023) highlighted that ternary blended systems generate a higher volume of hydration products, particularly C-S-H and calcium aluminosilicate hydrate (C-A-S-H), which enhance matrix densification. Likewise, (Hossain et al. 2023) reported that the interaction of RHA and WGP in PLC systems significantly refines pore structure and reduces permeability, leading to improved long-term performance.

The ITZ plays a critical role in determining the strength and durability of concrete(Li et al. 2023) investigating the inclusion of fine pozzolanic materials, such as RHA and WGP, improves the ITZ by filling micro-voids and strengthening the bond between aggregate and cement paste. (Islam et al. 2023) reported a reduction in micro-crack width and a more compact ITZ in ternary blended systems, particularly when fine materials are uniformly distributed.

Microstructural analyses using XRD and FTIR have shown that ternary blended cement systems alter the phase composition of concrete. (Zareei et al. 2022) found a significant reduction in calcium hydroxide peaks, indicating active pozzolanic reactions. Additionally, (Golewski 2023) reported an increase in stable hydration phases such as C-S-H and C-A-S-H, which contribute to improved structural integrity and durability.

At optimal replacement levels, the combined use of IFS and PLC, RHA, and WGP results in a dense and well-integrated microstructure. (Yüksel et al. 2023) confirmed that appropriate proportions lead to reduced pore size distribution and improved internal bonding. However, (Hossain et al. 2023) cautioned that excessive replacement of cement or aggregate can lead to incomplete hydration, increased porosity, and reduced performance due to the formation of weak zones.

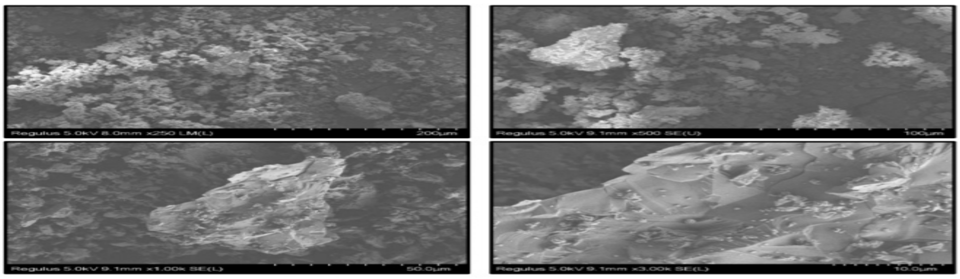

Plate 4: SEM Image of Induction Furnace Slag (Uzunömeroğlu et al., 2023)

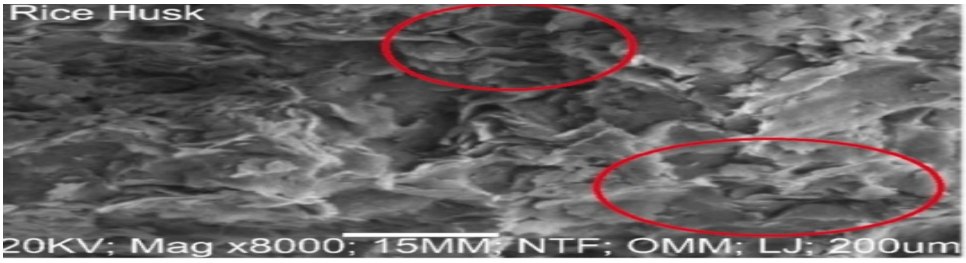

Plate 5: SEM Image for Rice Husk Ash (Olorunfemi et al., 2025)

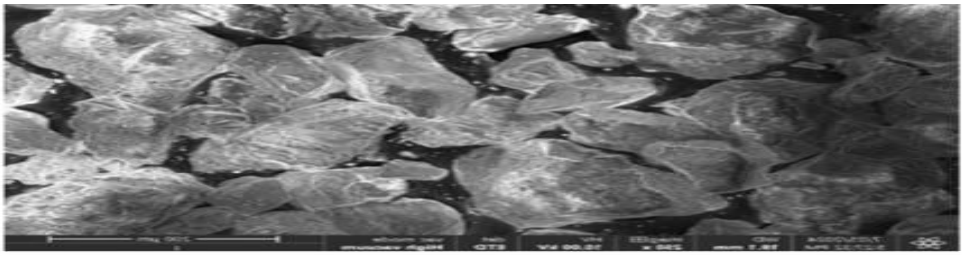

Plate 6: SEM Image for Waste Glass Powder (Akinpelu et al., 2025)

V. SUSTAINABILITY AND IMPLEMENTATION

Integrating PLC, RHA, and WGP in concrete production has been identified as an effective strategy for achieving sustainable construction while maintaining desirable engineering performance. (Dessie & Nuramo 2022) reported that WGP contributes to improved concrete durability due to its pozzolanic behavior and its ability to refine the pore structure of hardened cement paste. The suitability of RHA as a supplementary cementitious material was emphasized by (Alawi et al. 2026), who found that its high reactive silica content enhances strength development and reduces permeability in cement-based systems. PLC, RHA, and WGP system offers significant environmental advantages by utilizing waste streams (rice husks, glass) and limestone to displace high-carbon clinker production. Practical application suggests an optimal performance window when total SCM replacement remains below 30%, balancing workability, strength gain, and sustainable material use.

VI. RESEARCH GAPS

The following points outline key knowledge gaps in the current body of research concerning concrete systems that integrate IFS as aggregate with a novel ternary blended cement comprising PLC, RHA, and WGP.

1. There is an evident scarcity of studies simultaneously investigating IFS as aggregate in concretes containing ternary PLC, RHA, and WGP binders. While several researchers have evaluated the mechanical properties of IFS aggregate replacement and others have studied the benefits of RHA materials (SCMS) in binary or ternary blends, integrated studies combining systems are virtually absent. The lack of such multi-variable studies restricts the development of reliable mix-design procedures and limits understanding of potential synergistic or antagonistic interactions.
2. There is a significant gap in research that systematically links the macroscopic mechanical properties of these combined systems with rigorous microstructural evaluation techniques using SEM-EDS, XRD, TGA, MIP.
3. Comprehensive durability studies are notably absent for concretes containing both IFS aggregate and PLC, RHA, and WGP binders. Performance data regarding critical environmental exposure factors such as chloride ingress, carbonation, sulfate attack, and alkali-silica reaction (ASR) have not been adequately evaluated.
4. A substantial gap exists in the standardized characterization of RHA and WGP properties across different studies, making it difficult to generalize findings or develop region-specific design guidelines. Variations in waste source, combustion conditions, and grinding fineness led to highly variable chemical compositions, amorphous silica content, and particle size distributions.

VII. CONCLUSION

This review concludes that the incorporation of IFS as a partial replacement for natural aggregates within the range of approximately 20-50%, together with a ternary blended cement system comprising PLC, RHA at about 5-10%, and WGP at about 10-20% cement replacement levels, offers a viable pathway for the development of sustainable and high-performance concrete. At these optimal proportions, significant improvements in compressive, tensile, and flexural strengths are generally observed, primarily attributed to enhanced particle packing density, refined pore structure, and the synergistic pozzolanic reactions that promote additional calcium silicate hydrate (C-S-H) formation, thereby improving microstructural densification and ITZ quality. However, the literature consistently indicates that exceeding these optimum replacement levels may result in performance deterioration due to increased porosity, insufficient hydration products, and weakened aggregate-paste bonding. Therefore, the combined utilization of IFS, RHA, WGP, and PLC demonstrates strong potential for sustainable concrete production, although further investigation is required to optimize mix proportions and evaluate long-term durability performance under diverse exposure conditions.

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