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Utilization of Slate Powder in Concrete: A Review of Filler Mechanisms, Abrasion Resistance, and Microstructural Behaviour

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Abstract: The increasing demand for concrete and the continuous generation of stone-processing waste materials have encouraged researchers to investigate alternative materials for use in cementitious systems. Among various dimensional-stone wastes, slate powder generated during quarrying, cutting, and polishing operations has emerged as a potential filler material for concrete and related construction applications. The disposal of slate waste creates environmental and land-management concerns in slate-producing regions, thereby highlighting the need for effective utilization strategies.

The present review critically examines the available literature concerning the utilization of slate powder in concrete, mortar, geopolymer binders, asphalt mixtures, and other construction materials. The review focuses on the physical and mineralogical characteristics of slate powder and its influence on filler mechanisms, matrix densification, mechanical performance, abrasion resistance, durability behaviour, and microstructural properties of concrete systems. Previous investigations indicate that slate powder generally behaves as an inert or weakly reactive filler material contributing mainly through particle packing, pore refinement, and nucleation effects. Several studies reported improvement in compressive strength, tensile strength, and matrix compactness at lower replacement levels because of filler-induced densification, whereas higher replacement levels resulted in reduction of strength due to dilution effects.

The reviewed literature also establishes that abrasion resistance and durability behaviour are strongly related to matrix compactness, pore structure, and aggregate–paste bonding characteristics. However, direct investigations concerning abrasion resistance and long-term durability behaviour of slate powder concrete remain insufficient. The review further highlights the importance of detailed microstructural characterization because the behaviour of slate powder is strongly influenced by mineral composition, fineness, and source variation. Based on the reviewed studies, further experimental investigations are necessary to establish optimum utilization levels and evaluate the suitability of slate powder in structural concrete applications.

Keywords: Slate powder, concrete properties, filler effect, matrix densification, abrasion resistance, microstructure, cement replacement.

I. INTRODUCTION

Concrete is one of the most extensively used construction materials worldwide because of its versatility, strength, durability, and adaptability in different structural applications. Rapid urbanization and infrastructure development have significantly increased the demand for concrete over recent decades. However, the large-scale production of cement, which is the main binding material in concrete, is associated with considerable energy consumption and carbon dioxide emissions. These concerns have encouraged researchers to explore alternative materials that can partially replace conventional concrete constituents while maintaining satisfactory engineering performance.

In recent years, the use of industrial by-products and stone-processing wastes in concrete has received considerable attention. Materials such as marble dust, granite powder, quarry fines, limestone waste, and other fine mineral residues have been investigated for their suitability in concrete systems. Previous studies have shown that finely divided mineral fillers can improve particle packing, reduce void content, and enhance matrix densification in concrete at lower replacement levels.

Among the various stone-processing wastes, slate powder generated during quarrying, cutting, and polishing operations has emerged as a material of growing research interest. Slate is a fine-grained metamorphic rock mainly composed of silica-rich minerals such as quartz, feldspar, mica, chlorite, and aluminosilicate compounds.

During processing operations, significant quantities of fine slate powder are produced as waste material. In several slate-producing regions of India, including parts of Himachal Pradesh and Rajasthan, disposal of slate waste has become a concern because of land occupation and dust generation.

Several researchers have investigated the utilization of slate waste in different construction materials including autoclaved aerated concrete, ceramic products, geopolymer binders, cement mortars, asphalt mixtures, and concrete. Most studies indicate that slate powder mainly behaves as an inert or weakly reactive filler material. Improvements observed in concrete performance have generally been attributed to filler effects, improved packing density, and matrix refinement.

Although previous studies indicate the potential use of slate powder in concrete, the available literature remains comparatively limited when compared to other stone-processing wastes such as marble and granite powder. Therefore, a concise review of the available literature is necessary to understand the present state of research and identify important gaps requiring further investigation.

II. SLATE POWDER GENERATION AND CHARACTERISTICS

Large quantities of slate powder are generated during quarrying, cutting, dressing, polishing, and finishing operations associated with slate stone processing industries. During these operations, a considerable amount of fine waste material is produced in the form of slurry, dust, and cutting residues. In many slate-producing regions, particularly in parts of Himachal Pradesh, Rajasthan, and other hilly regions of India, disposal of such waste materials has become an important environmental and land-management concern. Improper dumping of slate waste contributes to dust pollution, blockage of drainage systems, and occupation of valuable land resources. Reports published by the Central Pollution Control Board (CPCB)[1–4] and the Indian Bureau of Mines (IBM)[5] indicate that dimensional stone industries generate substantial quantities of waste annually, a significant portion of which remains underutilized.

Slate is a fine-grained metamorphic rock formed under low-grade metamorphic conditions from shale-type sedimentary rocks. Mineralogical investigations indicate that slate generally contains silica-rich minerals such as quartz, feldspar, mica, chlorite, and aluminosilicate compounds. Because of the presence of these minerals, finely processed slate powder exhibits physical characteristics that make it suitable for use as a filler material in concrete and other cementitious systems. The fine particle size distribution of slate powder contributes to improved particle packing and matrix densification when incorporated at controlled replacement levels.

Campos et al.[6] (2004) characterized slate waste generated from slate processing industries and reported that the material predominantly consists of silica and alumina along with smaller quantities of iron oxides and other mineral constituents. Their investigation indicated that the fine nature of slate waste contributed to improved densification, bending strength, and wear resistance in structural ceramic products. Similarly, Astariani et al.[7] (2021) observed that slate stone powder contained significant quantities of silica and alumina, making the material suitable for geopolymer and filler-based applications. The study further reported denser microstructural behaviour in systems containing slate powder because of improved particle interaction within the matrix.

Several investigations indicate that untreated slate powder generally behaves as an inert or weakly reactive filler material rather than a highly pozzolanic supplementary cementitious material. Schuab et al.[8] (2020) reported that unprocessed slate waste did not exhibit significant pozzolanic activity, although improvements in compressive strength and matrix compactness were observed because of filler and nucleation effects. Similar observations have been reported in studies involving other inert silica-rich fillers where performance enhancement is governed mainly by physical densification mechanisms rather than strong chemical reactivity.

The behaviour of slate powder is strongly influenced by particle fineness, mineral composition, particle morphology, and source variation. Fine particles may occupy micro voids within the cement matrix and reduce pore connectivity, thereby contributing to refinement of the interfacial transition zone (ITZ). Previous investigations involving inert fillers have shown that such densification mechanisms can positively influence mechanical performance and durability-related properties of concrete systems.

Recent investigations have also explored the possibility of improving the reactivity of slate waste through thermal activation. Calderon-Morales et al.[9] (2024) reported that calcined slate waste developed improved pozzolanic characteristics because of the formation of amorphous phases during thermal treatment. X-ray diffraction analysis indicated mineralogical transformation after calcination, resulting in enhanced reactivity and improved cementitious behaviour. The study demonstrated that thermally activated slate waste may contribute not only through filler mechanisms but also through partial pozzolanic activity.

The reviewed studies collectively indicate that the behaviour of slate powder in concrete is strongly governed by fineness, mineral composition, source variation, and filler characteristics. Since these factors significantly influence matrix densification, durability behaviour, and mechanical performance, detailed characterisation of slate powder becomes essential before its practical utilization in structural concrete systems.

A comparative summary of previous investigations related to slate powder utilization in construction materials is presented in Table 1.

Table 1: Comparative Summary of Previous Studies on Slate Powder Utilization in Construction Materials

S. No	Author & Year	Material / Area	Key technical finding
1	Eden et al.[10] (1980)	Slate waste in autoclaved aerated concrete	Strength increased with density; slate-based AAC performed comparably to commercial AAC at similar densities
2	Campos et al.[6] (2004)	Slate waste in sintered structural tiles	High silica/alumina slate waste improved densification, bending strength, and wear resistance after sintering
3	Peng et al.[11] (2012)	Slate powder for ASR suppression	10–15% slate powder helped reduce ASR expansion when used with fly ash and silica fume
4	Morova et al.[12] (2016)	Slate waste powder as asphalt filler	75% SWP + 25% limestone gave maximum Marshall stability; 25% SWP + 75% limestone gave highest ITS
5	Singh Parihar & Upadhyay[13] (2020)	Review of slate powder waste in India	About 0.3 t waste per ton of processed slate; slate powder useful in tiles and pavers as filler or partial replacement
6	Schuab et al.[8] (2020)	Slate waste in Portland cement mortar	14% slate waste increased compressive strength by about 11.8%; non-pozzolanic; filler and nucleation effects dominated
7	Astariani et al.[7] (2021)	Slate stone powder geopolymer binder	USSP (~49% SiO_2, ~11% Al_2O_3) reached about 12.73 MPa at 28 days; denser microstructure with higher activator ratio
8	Astariani et al.[14] (2024)	Slate stone powder as concrete filler	2.5% replacement gave maximum compressive strength (32.84 MPa) and split tensile strength (7.93 MPa); denser matrix observed
9	Carrillo Beltran et al.[15] (2024)	Slate stone cutting sludges for geopolymer binders	Slate cutting sludge valorized through geopolymerization for binder development
10	Calderon-Morales et al.[9] (2024)	Heat-treated slate waste in Portland-composite cement	Calcined slate waste (600-1000°C) developed pozzolanic

			activity; 20% replacement gave 42.35 MPa and 84.93% Strength Activity Index
11	Calderon-Morales et al.[16] (2025)	Slate and marble waste as clinker substitutes	5-20% clinker replacement reduced CO2; 10-15% gave the best strength-sustainability balance

III. FILLER MECHANISMS AND MATRIX DENSIFICATION IN CONCRETE

The performance of concrete containing fine mineral fillers is strongly influenced by particle packing, pore refinement, and modification of the internal concrete microstructure. Previous investigations involving marble powder, granite dust, quarry fines, limestone fillers, silica-rich inert fillers, and other fine waste materials have demonstrated that finely divided particles may improve concrete performance through physical filling mechanisms rather than solely through chemical reactivity. The behaviour of slate powder in concrete is largely governed by similar mechanisms.

Concrete contains pores and voids of different sizes distributed within the cement paste, aggregate interface, and capillary pore network. When finely processed filler materials are introduced into the concrete matrix, the particles occupy micro voids present between cement grains and aggregate surfaces. This phenomenon is commonly referred to as the micro-filling or particle packing effect. Abbass et al.[17] (2019) explained that inactive silica fillers improve concrete behaviour primarily through reduction of internal porosity and enhancement of matrix compactness. The study emphasized that fine particles contribute to densification of the cement matrix even in the absence of strong pozzolanic activity.

Awoyera et al.[18] (2019) similarly reported that filler materials improve concrete performance by refining pore structure and reducing pore connectivity within hardened concrete. Fine particles improve the packing density of the system and reduce the volume of capillary voids, thereby contributing to a denser and more compact matrix. Hernandez-Carrillo et al.[19] (2022) also observed that inert fillers contribute to compact matrix formation in high-performance concrete systems through optimisation of particle distribution and reduction of pore spaces. These studies collectively indicate that filler efficiency depends strongly on particle size distribution, fineness, and surface characteristics of the incorporated material.

The behaviour of slate powder reported in previous investigations is consistent with these filler mechanisms. Astariani et al.[14] (2024) reported denser matrix formation and reduced pore spaces in concrete containing slate powder at lower replacement levels. The study observed improvement in compressive and split tensile strength because fine slate particles contributed to matrix densification and improved particle interaction within the concrete system. Similar observations were reported by Schuab et al.[8] (2020), who concluded that improvements observed in slate waste mortars were mainly associated with filler and nucleation effects rather than significant pozzolanic reactions.

In addition to particle packing, filler materials may also contribute through nucleation effects. Fine particles dispersed within the cement matrix provide additional surfaces for precipitation of hydration products. This accelerates the formation and distribution of hydration compounds around filler particles and contributes to refinement of the concrete microstructure. Schuab et al.[8] (2020) explained that fine slate particles acted as nucleation sites, thereby contributing to improved compactness and densification of the mortar matrix.

Another important mechanism associated with filler materials is refinement of the interfacial transition zone (ITZ). The ITZ is generally considered the weakest region in concrete because of higher porosity and weaker bonding between aggregate particles and cement paste. Fine fillers reduce porosity within this region and improve bonding characteristics between hydration products and aggregate surfaces. Hernandez-Carrillo et al.[19] (2022) reported that reduction in pore connectivity and improvement in matrix compactness contributed positively to durability-related behaviour in filler-incorporated concrete systems.

Although filler mechanisms contribute positively to concrete behaviour at lower replacement levels, excessive incorporation of inert fillers may eventually produce adverse effects because of dilution of cementitious content. Oti et al.[20] (2010) reported that higher replacement levels resulted in gradual reduction in compressive strength because the reduction in effective cement content became more dominant than the beneficial filler effect. Similar observations have been reported in studies involving quarry dust, marble powder, and granite fillers where optimum performance was generally achieved at controlled incorporation levels.

The influence of filler-induced matrix densification is also closely related to durability and abrasion behaviour of concrete. Reduced pore connectivity and denser microstructures generally contribute to lower permeability, improved surface compactness, and reduced material deterioration under abrasive conditions. Warudkar and Elavenil[21] (2020) reported that improved abrasion resistance in concrete is strongly associated with reduced porosity and improved aggregate–paste bonding. Similarly, Febin et al.[22] (2019) observed improvement in abrasion resistance and durability characteristics of filler-incorporated concrete because of pore refinement and reduction of internal voids.

The reviewed literature therefore indicates that the behaviour of slate powder in concrete is governed by the balance between beneficial filler-induced densification and adverse dilution effects at higher replacement levels. The efficiency of slate powder depends strongly on fineness, particle distribution, mineral composition, water demand, and replacement percentage. Consequently, detailed material characterisation and optimisation of replacement levels become essential for achieving satisfactory performance in slate powder-incorporated concrete systems.

A comparative summary of filler mechanisms and behaviour of different mineral fillers in concrete systems is presented in Table 2.

Table 2: Comparative Analysis of Filler Mechanisms and Behaviour of Mineral Waste Fillers in Cementitious and Concrete Systems

S.No	Author & Year	Non-slate filler or area	Key technical finding
1	Oti et al.[20] (2010)	Brick dust waste in concrete	10-20% replacement improved strength; higher replacement reduced strength and increased water demand
2	Abubaker[23] (2014)	Granite quarry dust in concrete	Up to 7.5% replacement did not reduce strength; higher levels caused gradual reduction
3	Bahoria et al.[24] (2018)	XRD of natural sand, quarry dust, waste plastic	Quartz and silica-bearing micro-fines act as inert fillers and improve densification
4	Febin et al.[22] (2019)	Quarry dust powder in concrete blocks	Compressive strength, abrasion resistance, and durability improved up to optimum levels due to reduced porosity
5	Awoyera et al.[18] (2019)[18]	Review of recycled fine materials as fillers	Fillers improve packing density, reduce porosity, and improve durability
6	Abbass et al.[17] (2019)	Active/inactive silica fillers in concrete	Ultrafine quartz improved strength at low dosage; silica fume gave stronger physical + pozzolanic effects
7	R et al.[25] (2020)	Granite dust + M-sand in concrete blocks	Optimum combination improved compressive, flexural, tensile, and durability performance
8	Hernandez-Carrillo et al.[19] (2022)	Limestone and quartz inert fillers in UHPC	High filler replacement still maintained strength and durability with adequate silica fume
9	Jain & Sancheti[26] (2023)	Silica fume + iron dust in HPC	At optimum dosage, strength improved and abrasion wear depth reduced
10	Koksal et al.[27] (2008)[27]	Silica fume + steel fibers in	Silica fume improved strength

		high-strength concrete	but reduced workability; steel fibers improved toughness and ductility

IV. ABRASION RESISTANCE AND DURABILITY BEHAVIOUR

Abrasion resistance is one of the most important durability-related properties of concrete surfaces exposed to mechanical wear and frictional forces. Concrete structures such as pavements, industrial floors, bridge decks, hydraulic structures, spillways, airport pavements, and heavy-duty flooring systems are frequently subjected to abrasive actions during service conditions. The abrasion behaviour of concrete is strongly influenced by matrix compactness, aggregate hardness, pore structure, surface quality, compressive strength, and characteristics of the interfacial transition zone (ITZ). Consequently, understanding the influence of filler materials on abrasion resistance becomes important while evaluating the long-term performance of concrete systems.

Previous investigations have shown that abrasion resistance is not governed solely by compressive strength but also by the quality of the near-surface concrete matrix. Dhir et al.[28] reported that abrasion behaviour is significantly affected by surface characteristics, curing conditions, aggregate properties, and internal porosity of concrete. The study emphasized that weaker surface mortar layers and higher pore connectivity contribute to increased material removal under abrasive conditions.

Warudkar and Elavenil[21] (2020), in their state-of-the-art review on abrasion resistance of concrete, reported that concrete possessing denser microstructures and reduced porosity generally exhibits improved resistance against surface wear. The review highlighted that abrasion resistance is strongly associated with improved aggregate–paste bonding, reduced pore connectivity, and enhanced matrix compactness. Similar observations were reported by Zhang et al.[29] (2025), who explained that lower water–cement ratio and pore refinement contribute significantly to improved abrasion performance in concrete systems.

The type and hardness of aggregates also play an important role in governing abrasion behaviour. Kilic et al.[30] (2008) investigated the influence of aggregate type on abrasion resistance of high-strength concrete and reported that harder aggregates generally produced better abrasion resistance and higher compressive strength. The study demonstrated that abrasion behaviour depends not only on the strength of the cement matrix but also on the mechanical properties of aggregate particles and the quality of aggregate–paste interaction.

Several studies involving filler materials have reported that pore refinement and matrix densification contribute positively to durability and abrasion-related behaviour. Febin et al.[22] (2019) observed improvement in abrasion resistance and durability characteristics of filler-incorporated concrete because of reduced porosity and improved matrix compactness. Similarly, Jain and Sancheti[26] (2023) reported reduction in abrasion wear depth at optimum incorporation levels of silica fume and iron dust due to densification of the concrete matrix and improvement in surface hardness.

The reviewed literature concerning slate powder indicates that lower replacement levels generally contribute to improved matrix compactness and reduction in internal voids because of filler effects. Astariani et al.[14] (2024) observed denser microstructures in concrete containing lower percentages of slate powder, indicating improved packing density and refinement of the internal matrix. Schuab et al.[8] (2020) similarly reported that slate waste particles improved matrix compactness through filler and nucleation effects. These observations suggest that slate powder may positively influence abrasion resistance through reduction in porosity and enhancement of surface compactness.

However, despite the increasing research interest in slate powder utilization, direct experimental investigations specifically evaluating abrasion resistance of slate powder concrete remain limited. Most available studies have focused primarily on compressive strength and general mechanical properties, whereas detailed investigations concerning abrasion loss behaviour, wear mechanisms, and long-term surface durability are still insufficient. In addition, limited studies are available correlating abrasion behaviour with SEM/XRD/EDS-based microstructural characterisation of slate powder concrete.

The reviewed literature therefore indicates that the relationship between slate powder incorporation, matrix densification, and abrasion resistance remains insufficiently explored, particularly in higher-grade structural concrete systems. Since abrasion behaviour is strongly associated with pore refinement, surface compactness, and interfacial bonding characteristics, further systematic investigations are necessary to establish clear relationships between filler behaviour and long-term durability performance of slate powder-incorporated concrete.

A comparative summary of previous studies related to abrasion resistance and durability behaviour of concrete systems is presented in Table 3.

Table 3: Comparative Analysis of Abrasion Resistance and Durability Behaviour of Concrete Incorporating Mineral Fillers and Waste Materials

S.No	Author & Year	Abrasion context	Key finding
1	Campos et al.[6] (2004)	Wear behaviour of slate-based structural tiles	Abrasion was identified as the primary wear mechanism; higher sintering temperature improved wear behaviour
2	Febin et al.[22] (2019)	Abrasion resistance of quarry dust concrete blocks	Abrasion resistance improved up to an optimum replacement because porosity decreased and microstructure densified
3	Dhir et al.[28] (n.d.)	Near-surface characteristics of concrete	Abrasion resistance depends strongly on surface layer quality, porosity, curing, and mix characteristics
4	Kilic et al.[30] (2008)	Aggregate type vs abrasion resistance in high-strength concrete	Harder aggregates gave better abrasion resistance and stronger concrete
5	Warudkar & Elavenil[21] (2020)	Review of abrasion resistance of concrete	Abrasion is governed by compressive strength, porosity, aggregate type, surface finish, and curing
6	Jain & Sancheti[26] (2023)	Silica fume + iron dust in HPC	Abrasion wear depth reduced by about 11.05% at optimum mix
7	Zhang et al.[29] (2025)	State-of-the-art review on abrasion resistance	Abrasion resistance improves with lower w/c ratio, denser matrix, and pore refinement

V. MICROSTRUCTURAL BEHAVIOUR AND CHARACTERISATION TECHNIQUES

Microstructural characterisation plays an important role in understanding the behaviour of slate powder and other mineral fillers in cementitious systems. The mechanical and durability performance of concrete is strongly influenced by internal pore structure, matrix compactness, hydration-product distribution, and the quality of the interfacial transition zone (ITZ). Consequently, characterisation techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and energy-dispersive spectroscopy (EDS) are widely used to evaluate the influence of filler materials on concrete microstructure.

Several investigations reported that incorporation of finely processed slate powder contributes to matrix densification and refinement of pore structure. Astariani et al.[7] (2021) observed comparatively denser microstructures in geopolymer systems containing slate stone powder because of improved particle interaction and reduced internal voids. Similar observations were reported by Astariani et al.[14] (2024), where lower replacement levels of slate powder resulted in improved matrix compactness and reduction in pore spaces within the concrete system. The studies indicated that fine slate particles contributed to better particle packing and improved distribution of hydration products within the matrix.

The densification behaviour observed in SEM analysis is closely related to filler-induced micro-filling mechanisms. Fine particles occupy voids present between cement grains and aggregate surfaces, thereby reducing pore connectivity and improving compactness of the hardened matrix. Schuab et al.[8] (2020) reported that improvements observed in slate waste mortar were mainly associated with filler and nucleation effects rather than significant pozzolanic reactivity. The study explained that fine slate particles acted as nucleation sites for hydration-product formation, thereby contributing to refinement of the microstructure.

The interfacial transition zone (ITZ) between aggregate particles and cement paste is generally considered the weakest region in concrete because of higher porosity and discontinuity in hydration products. Several studies involving inert fillers reported that fine particles improve the compactness of the ITZ by reducing microvoids and improving aggregate–paste interaction.

Hernandez-Carrillo et al.[19] (2022) explained that optimized filler incorporation contributes to reduction of pore connectivity and formation of denser matrices in high-performance concrete systems. Improved ITZ compactness may contribute positively to mechanical behaviour, abrasion resistance, and durability performance of concrete.

X-ray diffraction (XRD) analysis has also been widely used to evaluate the mineralogical composition and phase characteristics of slate powder. Campos et al.[6] (2004) reported that slate waste predominantly contains silica-rich and alumina-rich mineral phases along with smaller quantities of iron-bearing compounds. Similar mineralogical observations were reported in studies involving slate stone powder and calcined slate waste systems. The silica-rich nature of slate powder contributes to its suitability as a filler material in cementitious applications.

Recent investigations have explored the possibility of improving the reactivity of slate waste through thermal activation. Calderon-Morales et al.[9] (2024) reported that calcination of slate waste resulted in transformation of crystalline mineral phases into comparatively amorphous structures with improved pozzolanic behaviour. XRD analysis conducted in the study indicated mineralogical changes after thermal treatment, contributing to improved reactivity and cementitious performance. These findings suggest that untreated slate powder generally behaves as an inert filler material, whereas thermally activated slate waste may partially contribute through pozzolanic mechanisms.

Energy-dispersive spectroscopy (EDS) analysis has further been used to evaluate elemental composition and distribution within slate powder systems. Previous investigations reported the presence of silica, alumina, iron, and other mineral constituents contributing to filler behaviour and matrix densification. Variations in elemental composition may occur because of differences in geological origin and processing methods, thereby influencing the behaviour of slate powder in cementitious systems.

The reviewed literature collectively indicates that the microstructural behaviour of slate powder concrete is strongly governed by fineness, mineral composition, particle morphology, and replacement level. Lower incorporation levels generally contribute to reduction of pore spaces, improved matrix compactness, and refinement of the interfacial transition zone, whereas excessive replacement levels may increase porosity because of cement dilution effects. The relationship between microstructural refinement and abrasion resistance also indicates that denser matrices with reduced pore connectivity may exhibit improved surface durability characteristics.

Despite the increasing research interest in slate powder utilization, detailed studies correlating SEM, XRD, and EDS observations with abrasion resistance and long-term durability behaviour remain inadequately investigated. Most available investigations focus primarily on compressive strength and general mechanical properties, whereas comparatively fewer studies examine the combined relationship between microstructural characteristics and surface wear behaviour in slate powder-incorporated concrete systems.

VI. RESEARCH GAPS AND FUTURE RESEARCH DIRECTIONS

1) The reviewed literature indicates that slate powder possesses significant potential for utilization in concrete and other construction materials because of its filler characteristics and matrix densification behaviour. Several investigations reported improvement in mechanical performance and compactness at lower replacement levels due to particle packing and pore refinement mechanisms. However, despite the growing interest in slate powder utilization, the currently available literature remains relatively few, when compared with studies involving other mineral fillers such as marble powder, granite dust, silica-rich fillers, and quarry fines.
2) Most of the available investigations concerning slate powder primarily focus on compressive strength behaviour and general mechanical performance, whereas comparatively fewer studies are available regarding abrasion resistance and long-term durability characteristics. Abrasion behaviour is strongly influenced by matrix compactness, aggregate–paste bonding, pore structure, and surface quality, yet limited experimental investigations have specifically examined the abrasion resistance of concrete incorporating slate powder. Existing studies involving filler materials indicate that reduced porosity and improved matrix compactness may positively influence abrasion behaviour; however, detailed studies directly correlating slate powder incorporation with abrasion performance remain insufficient.
3) The reviewed literature also indicates considerable variation in optimum replacement levels reported by different researchers. These variations are mainly associated with differences in mineral composition, fineness, source characteristics, particle morphology, curing conditions, and mix proportioning approaches. Because slate powder obtained from different geological sources may exhibit different physical and mineralogical characteristics, detailed material characterisation becomes important before practical utilization in concrete systems.

4) Although several investigations discussed matrix densification and filler behaviour, comparatively limited studies are available correlating mechanical and durability performance with SEM, XRD, and EDS-based microstructural observations. Most studies focus primarily on compressive strength evaluation without establishing detailed relationships between pore refinement, interfacial transition zone behaviour, and long-term durability characteristics. Similarly, the influence of slate powder on higher-grade structural concrete systems remains comparatively underexplored in the available literature.
5) Recent investigations concerning thermally activated slate waste indicate the possibility of improved pozzolanic behaviour after calcination. However, further studies are still required to evaluate the practical feasibility, durability behaviour, and long-term performance of activated slate waste systems under different curing and exposure conditions.
6) Based on the reviewed studies, future investigations should focus on detailed characterisation of slate powder obtained from different geological sources and its influence on concrete behaviour under varying replacement levels. Additional studies concerning abrasion resistance, long-term durability, higher-grade concrete applications, and combined microstructural-performance relationships are necessary for establishing the practical suitability of slate powder in structural concrete systems.

VII. CONCLUSION

1) Large quantities of slate powder are generated during quarrying, cutting, dressing, and polishing operations associated with slate processing industries, creating disposal and land-management concerns in slate-producing regions.
2) The reviewed literature indicates that slate powder contains silica-rich and alumina-rich mineral phases, making it suitable for utilization as a filler material in concrete and other cementitious systems.
3) Most studies reported that untreated slate powder generally behaves as an inert or weakly reactive filler material, contributing mainly through particle packing, pore refinement, and matrix densification mechanisms.
4) Lower replacement levels of slate powder generally improved matrix compactness and mechanical performance because fine particles occupied internal voids and refined pore structure within the concrete matrix.
5) Several investigations reported improvement in compressive strength, split tensile strength, and microstructural compactness at controlled replacement levels because of filler and nucleation effects.
6) Higher replacement levels generally resulted in reduction of mechanical performance because cement dilution effects became more dominant than the beneficial filler action.
7) Studies involving SEM analysis indicated denser microstructures and reduced pore connectivity in systems containing lower percentages of slate powder.
8) XRD and EDS investigations confirmed the presence of silica, alumina, and other mineral constituents influencing the behaviour of slate powder in cementitious systems.
9) Recent investigations on calcined slate waste reported improved pozzolanic behaviour because of mineralogical transformation during thermal activation.
10) The reviewed literature also established that abrasion resistance and durability behaviour are strongly associated with matrix compactness, pore structure, and interfacial transition zone characteristics.
11) Existing studies involving filler materials suggest that reduced porosity and improved matrix densification may positively influence abrasion resistance behaviour; however, direct abrasion-related investigations on slate powder concrete remain scarcely explored.
12) Considerable variation in optimum replacement levels reported by different studies indicates that the behaviour of slate powder is strongly influenced by fineness, source variation, mineral composition, and processing characteristics.
13) The reviewed studies collectively indicate that slate powder possesses promising potential for utilization in concrete and related construction materials, particularly as a filler material contributing to matrix densification and compactness.
14) Further investigations concerning abrasion resistance, long-term durability, higher-grade concrete applications, and combined microstructural-performance relationships are still required for establishing the practical suitability of slate powder in structural concrete systems.

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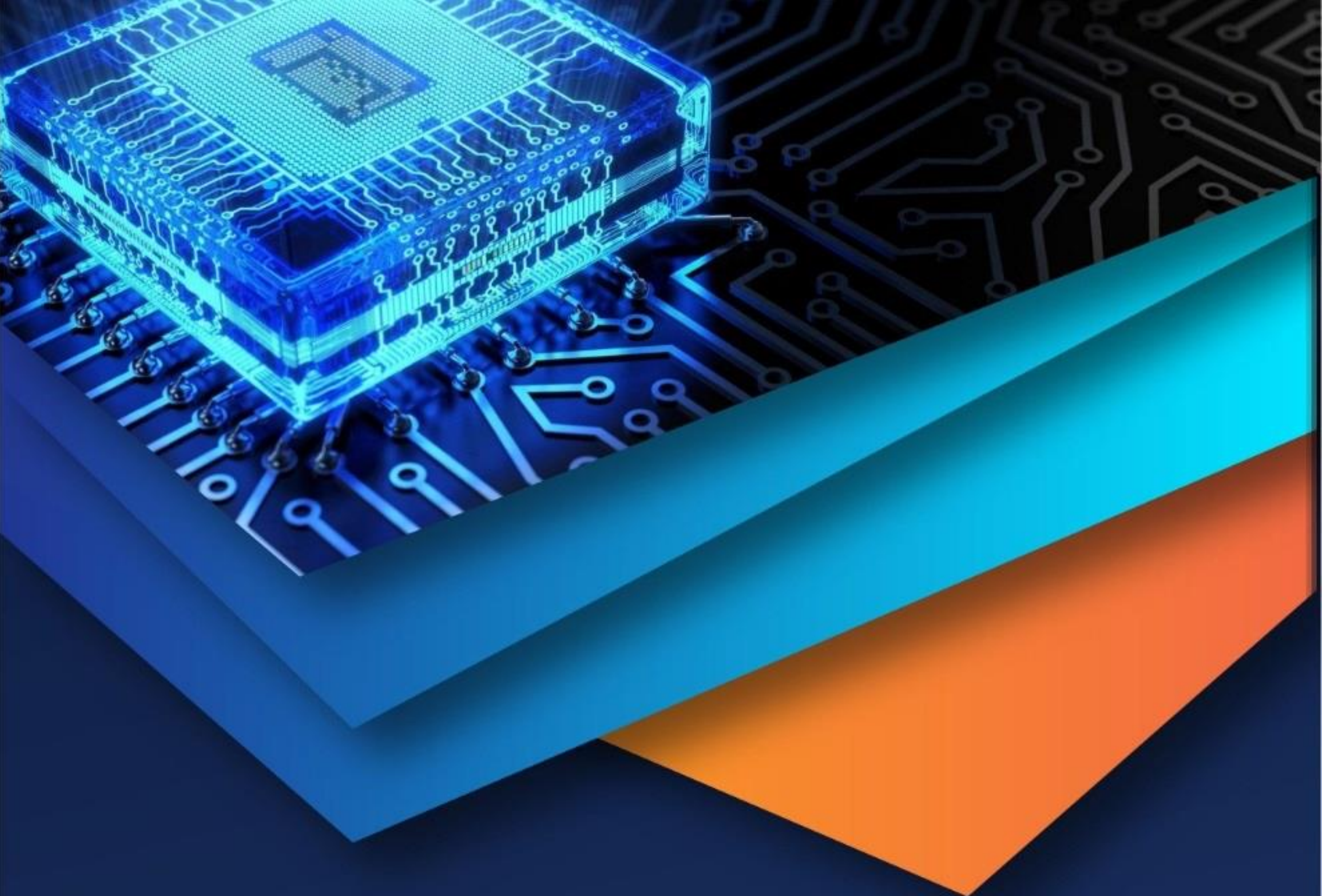

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