



Exploring fly ash and quarry dust particles for next generation anodized coatings

Norliyana Mustapar ¹, Shahira Liza Kamis ^{1*}, Kanao Fukuda ¹, Noor Ayuma Mat Tahir ¹, Yazid Yaakob ²

¹ Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia, MALAYSIA.

² Halal Products Research Institute, Universiti Putra Malaysia, MALAYSIA.

*Corresponding author: shahiraliza@utm.my

| KEYWORDS | ABSTRACT |
|--|---|
| Industrial waste Anodic oxide coating Hardness Friction Wear | The sustainable utilization of industrial waste into anodic oxide coating presents a promising route for developing high-performance surface coatings while addressing environmental concerns. Despite growing interest, comprehensive understanding of their properties and role in improving mechanical and tribological performance remains limited. This review highlights the potential of Fly Ash with a predominantly spherical morphology, and Quarry Dust with an angular morphology. Both are rich in silica and alumina, containing quartz and mullite phases, and exhibit excellent thermal stability. Their incorporation reduces porosity, enhanced hardness, and wear resistance, making them highly suitable for high-performance applications. The findings underscore industrial waste as a viable, and sustainable reinforcement material. |

1.0 INTRODUCTION

Anodizing offers numerous advantages, including improved surface hardness, corrosion resistance and aesthetic appeal (Mathew et al., 2016; Paz Martínez et al., 2020). However, it also presents inherent limitations such as porosity and microcracks, which compromise the surface coating quality and durability (Asquith et al., 2006; Ma et al., 2013; Wu et al., 2017). To overcome these issues, researchers have explored the incorporation of reinforcement particles into the anodic oxide coating (Kamada et al., 2005; Li et al., 2015; Aziz et al., 2024; Muktar et al., 2024). Conventional anodic oxide coatings typically rely on high-purity ceramic powders or synthetic compound that are energy-intensive to produce and often involve mining of non-renewable

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resources (D. Zhang et al., 2013; Li et al., 2015). These materials can be expensive, resource-depleting, and in some cases hazardous to health or the environment due to heavy metal content or processing emissions (Tao et al., 2023; Ma et al., 2021). In addition, the high cost of advanced coatings limits their accessibility in many industrial sectors, particularly where large surface areas or cost efficiency is critical.

Given these limitations, researchers are exploring the use of industrial waste (Gaurav Arora et al., 2018; E.C. Ailenei et al., 2021; Ghani et al., 2021). In recent decades, several countries have undertaken significant efforts toward the utilization of industrial waste materials as reinforcements in the development of eco-friendly and sustainable engineering materials (Senthamarai et al., 2011; Kishore et al., 2020). This shift aims to reduce environmental impact, lower production costs, and promote circular economy practices by transforming industrial waste into value-added components for advanced material applications. The usage of industrial waste dates back to ancient times when by-products from thermal power plant, mining, and quarrying were repurposed for construction industries, such as substitute for fine aggregate in construction activities (Sukesh et al., 2013; Rai et al., 2014). The utilization of industrial waste offers numerous benefits from environmental, material performance, and process efficiency perspectives (De Queiroz Lamas et al., 2013; Simboli et al., 2014). Industrial waste materials often exhibit a good mechanical strength, and intrinsic chemical stability, making them excellent candidates for reinforcement in composites and surface coatings (Rajput et al., 2022; Kapgate et al., 2024). They can enhance specific strength and load-bearing capacity while offering simple processing routes because of their natural compatibility with electrolyte solution and ease of incorporation (Sharma et al., 2024; Norbidin et al., 2024). Furthermore, their use supports cost-effective and sustainable production.

Fly ash (FA) and quarry dust (QD) are two of the industrial waste available abundantly in many countries, including Malaysia. Recognizing the environmental impact of industrial waste disposal, Malaysia has implemented policies such as the Eleventh Malaysia Plan and initiatives under the Green Technology Master Plan Malaysia 2017–2030 to promote sustainable development strategies. These initiatives encourage the valorization of industrial waste in construction and manufacturing, aligning with the nation's broader goals for a circular economy, and these regulatory frameworks support research and industrial adoption of waste-based materials. FA (from thermal power plant activities) and QD (from quarrying activities) possess favorable physical and chemical characteristics, such as high SiO_2 and Al_2O_3 content, thermal stability, and fine particle size, that make them suitable as reinforcement or base materials in surface coating systems (J. Barroso et al., 2007; P. Shanmughasundaram et al., 2011). Studies from the early 2015s primarily focused on bulk construction applications, while recent research (2020–present) has shifted toward more advanced uses, including the incorporation of these wastes into composites, surface coatings, and functional materials, reflecting a growing interest in high-value reuse strategies. Figure 1 depicts the annual publication count since early 2015s, according to Science Direct (Elsevier) data, indicating a significant increase in researcher interest in the use of FA and QD across various applications, likely due to their benefits.

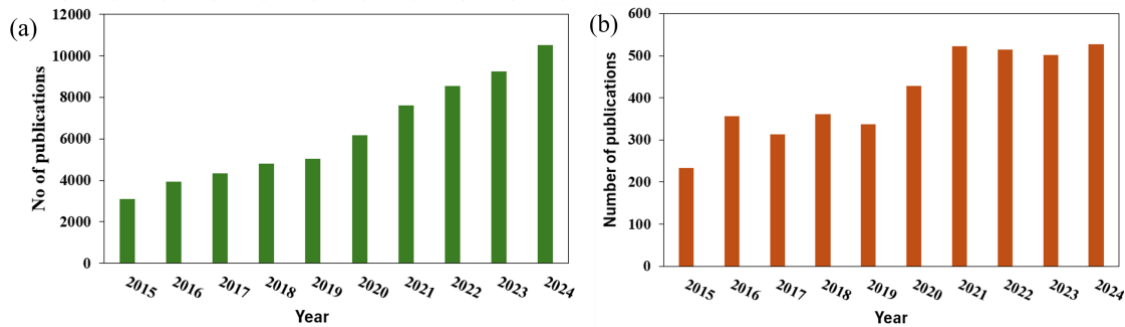


Figure 1: Number of publications of (a) FA and (b) QD per year from 2015 to 2024 according to science direct data. Source: <https://sciedirect.com>. Keyword used: (a) FA (b) QD.

Therefore, this review explores the overview and physicochemical characteristics of FA and QD, as well as the incorporation of both waste materials into anodic oxide coatings in a detailed manner. This review will assist researchers working in industrial waste and surface coating industries.

2.0 FLY ASH AND QUARRY DUST PARTICLES

2.1 Overview of FA and QD Particles

Among various industrial waste, FA and QD have emerged as two of the most abundant and promising waste materials with various applications (Zhao et al., 2020; Song et al., 2021; Sundaralingam et al., 2022; Febriansyah et al., 2024). FA is industrial residue deriving from the heating and combustion of coal in thermal power plant (Saikia et al., 2021; Ahmed et al., 2021). The formation of FA occurs in thermal power plants during the combustion of pulverized coal in a suspended state within the furnace, enabling efficient burning of the combustible components (as shown in Figure 2). During this high-temperature process, the non-combustible mineral matter in the coal, primarily ash, becomes entrained in the flue gas stream (Turuallo et al., 2016; Nayak et al., 2022). Some of this ash partially melts due to the intense heat, and under the influence of surface tension, forms numerous fine spherical particles. As the flue gas carrying these particles moves toward the boiler's tail end, driven by the induced draft fan, it experiences a temperature drop, causing some of the molten particles to rapidly cool and solidify into a glassy, amorphous structure with high potential reactivity. Prior to the flue gas being released into the atmosphere, these fine spherical particles are captured by electrostatic precipitators or baghouse filters, resulting in the collection of FA (Thomas et al., 2013; Jaworek et al., 2021; Sahu et al., 2021).

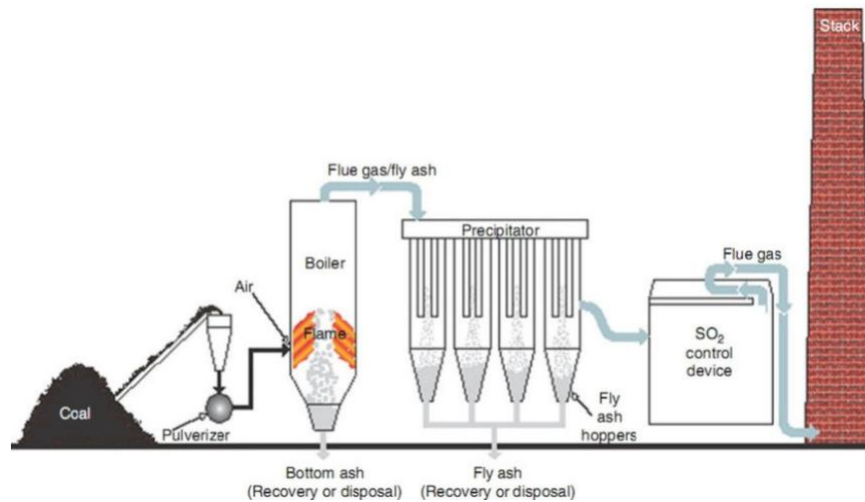


Figure 2: Schematic diagram of production of FA (Turuallo et al., 2016).

On another hand, QD is a by-product of the crushing process in quarrying operations (Galetakis et al., 2012; Pradhananga et al., 2020; Cheah et al., 2022). Crushing rocks into smaller sizes for construction aggregates or road base materials results in the generation of a significant amount of fine particulate matter. These fine particles are collected and utilized as QD (Jagadeesh et al., 2016; Othman et al., 2018). Owing to its high SiO₂ content, angular shape, high surface area, and mineralogical similarity to natural sand, QD has garnered interest for incorporation into construction materials (Ephraim et al., 2012; Prathipati et al., 2022). QD is commonly used as a partial replacement for cement, concrete product and building/structural block mixes due to its pozzolanic properties (Lohani et al., 2012; Sukesh et al., 2013). Overall, both of these materials (FA and QD) are generated in substantial quantities and, if left unutilized, contribute to significant environmental degradation through dust emissions, land use, and leaching concerns. Furthermore, this review paper will further explain FA and QD, with their numerous advantageous properties (which will be discussed further in the next section), due to their potential to enhance the mechanical and tribological performance of surface coatings (Dana et al., 2004; Othman et al., 2018).

2.2 Physicochemical Properties of FA and QD Particles

An understanding of physicochemical properties facilitates improved material selection and processing strategies, leading to enhanced performance in diverse functional and protective coating applications. FA is typically composed of fine and spherical particles shapes (as shown in Figure 3) (Sarkar et al., 2012; Kolay et al., 2014). The spherical morphology of FA particles is particularly advantageous for anodizing applications, especially when used as a reinforcement in particle-suspended electrolytes or post-anodizing impregnation processes. This spherical morphology also contributes to a high packing efficiency within the porous anodic oxide layer, allowing for effective pore filling, which in turn enhances the coating density, hardness, and wear resistance (Liu et al., 2022). Additionally, the smooth surface and shape of FA particles reduce the overall viscosity of the slurry in suspension-based processes, ensuring better flow dynamics and particle transport under the influence of the applied electric field. The particle size distribution,

typically between 1–50 μm , further supports their incorporation into the porous structure (Salah et al., 2016; Liu et al., 2017). On another note, QD exhibits a more angular (Figure 4), irregular morphology, with particle sizes typically ranging from 10 to 100 μm , although further size refinement through milling or sieving can improve compatibility with finer coating systems (Yap et al., 2020; Jumahat et al., 2024; Shagwira et al., 2024). The angular shape of QD particles enhances mechanical interlocking within the coating matrix, especially in binder-rich systems like polymer-based coatings, leading to improved adhesion strength and resistance to delamination under mechanical stress (Sharma et al., 2021; Nuruzzaman et al., 2024).

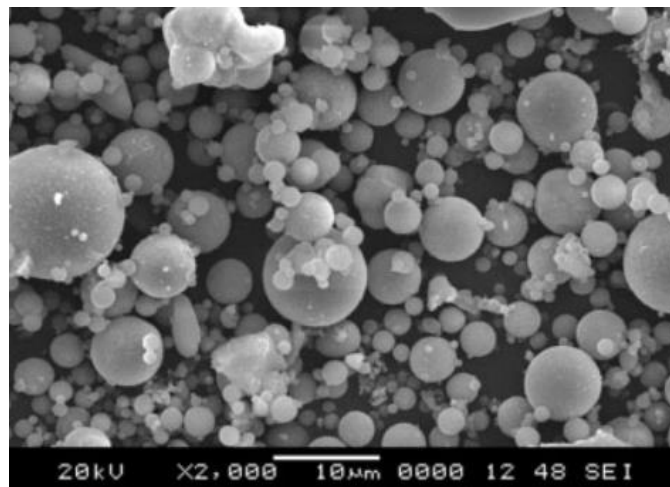


Figure 3: SEM image of (a) FA powder (Shiri et al., 2016).

Besides that, FA and QD consist of same multiple composition, primarily comprising SiO_2 and Al_2O_3 . These materials possess a phase structure of quartz and mullite, which can contribute to the enhanced hardness of the surface coating (Dana et al., 2004; Yaping et al., 2008; Yap et al., 2020). Quartz exhibits a crystalline structure, with its crystal structure consisting of interconnected SiO_2 tetrahedral (Götze et al., 2021). The strong covalent bonds between Silicon (Si) and oxygen (O_2) atoms contribute to the hardness properties (Chowaniec et al., 2022). Quartz phase also denotes a well-ordered structure (Garcia et al., 2018) that can resist deformation under mechanical load. Likewise, the crystal structure of mullite involves the combination of SiO_2 and Al_2O_3 , creating a unique lattice structure that enhances the overall hardness of the FA and QD particles (Roy et al., 2021). Mullite phase is inherently more complex than quartz phase due to its unique structure, which combines Al and silicon that contributes to exceptional thermal and mechanical resilience (Lima et al., 2022). The complex atomic arrangement in mullite phase, compared to the simpler structure of quartz phase, enables it to withstand high temperatures and mechanical stresses more effectively. According to literature, mullite can be a suitable alternative to commercial ceramic materials like Al_2O_3 and SiO_2 in the preparation of composites. This is due to the high aluminosilicate content, as well as its superior thermal resistance, low thermal expansion/conductivity, and impressive chemical and mechanical stability (Moreno et al., 2015; Mahnicka-Goremikina et al., 2018; Mahnicka-Goremikina et al., 2020; Kurovics et al., 2021). Mullite also has an excellent thermal characteristic, which is high specific heat capacity (around 4.22 J/g. K) (Roy et al., 2021). Hence, mullite can absorb and store more heat without a significant

increase in temperature (Choo et al., 2019; Cao et al., 2024), this helps maintain temperature stability in environments where heat is generated, during anodizing process.

Other than that, FA and QD have the potential to be used as reinforcement, largely attributed to their rich content of Al_2O_3 and SiO_2 , both widely recognized for their outstanding mechanical strength, thermal stability, and wear resistance when used individually as commercial ceramic reinforcements. Commercially available SiO_2 and Al_2O_3 have consistently delivered favorable results in enhancing coating performance, particularly in improving hardness and tribological behavior (D. Zhang et al., 2013; Lu et al., 2016; Ghafaripoor et al., 2018). Based on previous researchers (Nadimi et al., 2022), have highlighted the advantages of incorporating SiO_2 particle in the surface coating. The addition of SiO_2 particles improved the porosity of the coating and resulted in a more uniform structure. Less porosity on the surface limits the penetration of corrosive solution and reduce surface roughness of the coating, ultimately enhancing surface hardness and wear resistance. In addition, a study by Chen et al. (Chen et al., 2010) showed that anodic oxide coating on Al alloy with the addition of Al_2O_3 particles improved hardness and wear resistance, where the particles fill in the pores of the oxide coating. When these two oxides are present together, as naturally combined in FA and QD, they offer a synergistic effect that can further strengthen the coating matrix (Alaneme et al., 2018; Othman et al., 2019; Febin et al., 2019; Folorunso et al., 2019). The simultaneous presence of SiO_2 and Al_2O_3 promotes surface densification, minimizes porosity, and enhances load-bearing capacity (Othman et al., 2018; Mat tahir et al., 2022). Therefore, coatings reinforced with FA and QD exhibit superior mechanical integrity and tribological performance. This finding corroborates the aforementioned claim. Furthermore, the utilization of FA and QD aligns with sustainable practices, offering an economical and eco-friendly alternative to commercial ceramic particles.

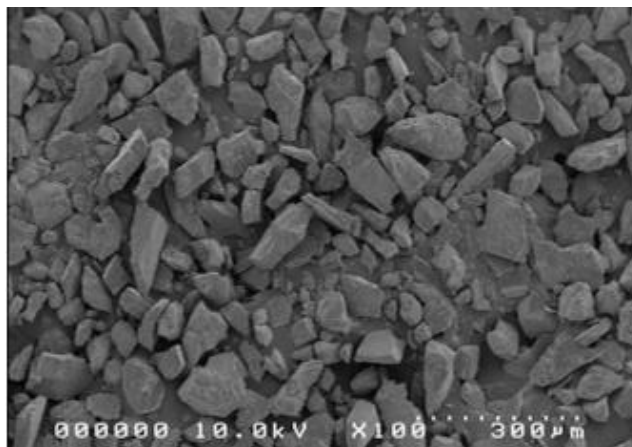


Figure 4: SEM image of QD powder (Ngugi et al., 2024).

The unique physicochemical attributes of FA and QD, such as particle size and shape, morphology, multiple chemical composition (as shown in Table 1), thermal behavior, and phase structure, collectively determine their effectiveness as reinforcements particles in surface coatings. When optimized, these properties not only improve mechanical hardness, thermal resistance, and wear behavior, but also contribute to sustainability by reducing reliance on high-cost ceramic powders or synthetic additives. Table 2 represents summary physical properties of FA and QD.

Table 1: Chemical composition of FA and QD (Othman et al., 2018; Lăzărescu et al., 2019).

| Composition | FA | QD |
|--------------------------------|-------------------|------|
| | Concentration (%) | |
| SiO ₂ | 53.61 | 72.6 |
| Al ₂ O ₃ | 26.16 | 15.1 |
| Fe ₂ O ₃ | 7.58 | 1.9 |
| CaO | 2.42 | 1.1 |
| MgO | 1.49 | 0.8 |
| SO ₃ | 0.26 | 0.2 |
| Na ₂ O | 0.59 | 3.0 |
| K ₂ O | 4.9 | - |

Table 2: Physical properties of FA and QD.

| Properties | FA | QD | Relevant to Surface coating application |
|-----------------------|-----------------------------|--|--|
| Particle size | 1-50 μm | 10-100 μm | Determines pore filling, surface uniformity, and dispersion (Sanalkumar et al., 2019; Mohamad et al., 2020; Zulkifli et al., 2023) |
| Particle morphology | Spherical | Angular (irregular) | Affects surface roughness and pores filling (Bahramian et al., 2015; N.Niraj et al., 2018; Sharma et al., 2021) |
| Specific surface area | 300-500 m ² /kg | 50-150 m ² /kg | Influences mechanical interaction (Montes et al., 2009; Dorigato et al., 2012; Meloni et al., 2012) |
| Bulk density | 0.54-0.86 g/cm ³ | 1.6-1.9 g/cm ³ | Impacts coating weight and particle incorporation efficiency (Annigeri et al., 2018; Liu et al., 2022) |
| Phase structure | Quartz, mullite | Quartz, mullite | Enhance hardness and wear resistance (D.Zhang et al., 2013; Mustapar et al., 2024) |
| Thermal stability | High (up to ~1000 C) | High (depends on chemical composition) | Suitable for high-temperature or frictional wear environments (Cai et al., 2016; Ma et al., 2021) |

3.0 COMPOSITE OXIDE COATING (FA-REINFORCED ANODIC OXIDE COATING AND QD-REINFORCED ANODIC OXIDE COATING)

3.1 Mechanical Properties

The incorporation of these ceramic-rich particles (FA), known for their high hardness and thermal stability, primarily due to the presence of quartz and mullite phases, significantly improves the tribological properties of the coating (Mat Tahir et al., 2022; Mustapar et al., 2024). These hard particles act as load-bearing reinforcements, reducing the direct contact between the softer aluminum substrate and external abrasive surfaces (Chauhan et al., 2013; Zulkifli et al., 2023). Moreover, the pore-filling effect (as shown in Figure 5) leads to a denser and more

homogeneous coating, which contributes to improved microhardness (up to 116.9%), reduced surface roughness, and enhanced wear resistance (Díez-pascual et al., 2019; Md. Ghazazi et al., 2023; Mustapar et al., 2024). This densification process mitigates common defects such as microcracks and porosity, which are typical failure initiation sites under cyclic or sliding loads. D. Zhang et al. (D.Zhang et al., 2013) made similar observation. The finding reveals that reinforcement particles successfully embedded into the pores (as per Figure 6a), thus increase surface hardness of the anodized coating. The enhanced surface hardness is a result of Al_2O_3 particles being introduced into the micro-pores and distributed throughout the anodic oxide coating, which strengthens the anodized film matrix. Mustapar et al. (Mustapar et al., 2024) also supported these findings by SEM micrograph that proved the presence of SiO_2 particles inside the anodic oxide coating (as shown in Figure 6b) helped increase the surface hardness of anodic oxide coatings by 89.5 % compared to unreinforced coatings (0 g/L). The lower microhardness observed in the unreinforced coatings (0 g/L), relative to the reinforced anodic oxide coating, is attributable to its greater surface porosity. Such porosity is known to diminish a materials surface strength and ductility. Therefore, the reduced surface hardness and increased porosity suggest a comparatively weakened structure.

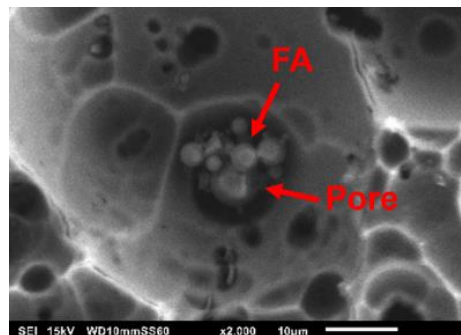


Figure 5: Surface morphologies of 100 g/L FA reinforced oxide coating (Mustapar et al., 2024).

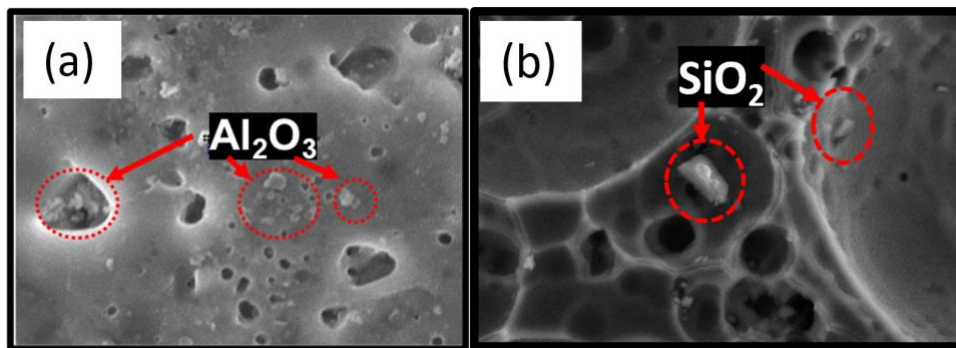


Figure 6: Surface morphologies of composite oxide coating containing (a) Al_2O_3 particles (D. Zhang et al., 2013) and (b) SiO_2 (Mustapar et al., 2024).

3.2 Tribological Performance

The incorporation of FA particles into anodic oxide coatings has shown substantial improvement in tribological performance (Mat Tahir et al., 2022; Mustapar et al., 2024). One of

the most notable effects is the enhancement in wear resistance, as these reinforcements contribute to the mechanical integrity of the oxide layer by filling the pores and increasing coating density. FA, with its spherical morphology and aluminosilicate composition (as mentioned in subsection 2.2), promotes a more compact structure that can resist crack propagation and distribute applied load more evenly. Consistent with these observations, Mat Tahir et al. (2022) highlighted that incorporating FA as a reinforcement in composite oxide coatings leads to a reduction in the wear rate, particularly when FA content is increased (Figure 7). Their research demonstrated a 28.8% decrease in the wear rate for FA-reinforced composite oxide coatings compared to the unreinforced anodic oxide coating. This aligns with previous studies, which indicate that the inclusion of reinforcement in oxide coatings enhances hardness, thereby lowering the wear rate (Liu et al., 2021; Priyadarshi et al., 2022; Zhang et al., 2022; Köse et al., 2025). According to our previous studies (Mustapar et al., 2024), the wear rate decreased by approximately 65.21% compared to the unreinforced anodic oxide coating. This improvement can be attributed to the enhanced surface coating hardness and the presence of a transfer layer, both of which play a crucial role in protecting the surface coating and, consequently, lowering the wear rate.

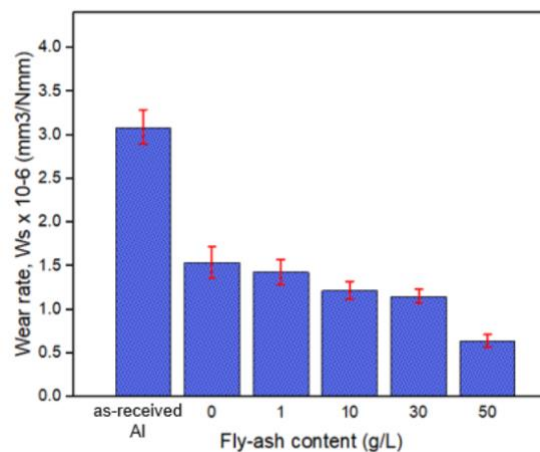


Figure 7: Wear rate of as received and anodized Al with different FA content (Mat Tahir et al., 2022).

On the other hand, in terms of coefficient of friction (COF), anodic oxide coatings reinforced with FA generally exhibit lower (up to 13.2%) (Mustapar et al., 2024) and more stable friction values compared to unreinforced anodic oxide coating (as shown in Figure 8). This is due to the reduced formation of abrasive oxide debris and the smoother surface finish achieved through effective pore filling. Additionally, the improved surface roughness from FA-reinforced anodic oxide coatings facilitates contribute to stable tribological behavior. Industrial waste-reinforced anodic oxide coatings have also demonstrated significant increases in microhardness, often exceeding 450 HV (Azam et al., 2019; Mustapar et al., 2024), depending on the reinforcement type and content, providing better resistance to plastic deformation and surface wear during rotational motion.

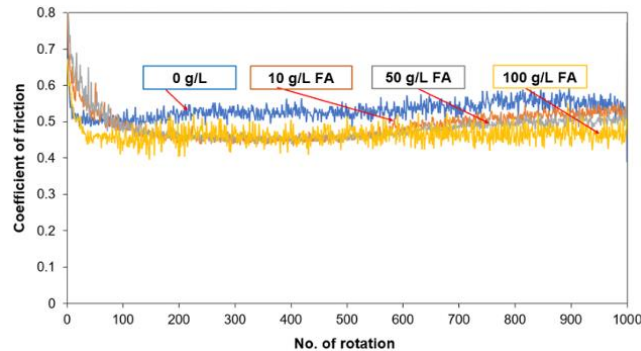


Figure 8: Coefficient of friction for anodic oxide coating at different FA content (Mustapar et al., 2024).

Despite the relatively limited number of studies exploring the utilization of FA and underexplored QD in surface coating technologies, growing evidence suggests that such materials possess substantial untapped potential for broader and large-scale applications. FA and QD offers a unique combination of advantages such as abundant availability, low cost, desirable physicochemical properties (as discussed in subsection 2.2) and reduced environmental impact, that align with the core principles of sustainable materials engineering and circular economy frameworks. Their inherently high thermal stability, mechanical strength, and chemical inertness make them suitable candidates for reinforcing surface coatings in demanding environments. It is worth to highlight that these beneficial properties of FA and QD have already led to its successful application in other surface coating techniques, such as in electroplating processes. Previous researchers comprehensively examined the wear performance of electroless nickel-based composite coatings reinforced with FA and QD (Othman et al., 2018; Azam et al., 2019). In the case of QD-reinforced Ni-P coatings, the incorporation of QD due to its rich in SiO_2 and Al_2O_3 enhanced wear resistance, with the optimal performance observed at a concentration of 60 g/L. This improvement was attributed to the mechanical interlocking of the hard QD particles, which increased hardness and durability of the coating (Azam et al., 2019). This finding is also supported by authors (Ramesh et al., 2014), who observed that the hard reinforced particles offered resistance to surface plastic deformation during the indentation, while QD particles imparted their inherent hardness property to the soft matrix, significantly increasing the overall hardness of the composite. In parallel, FA-reinforced Ni coatings showed significant enhancements in wear performance as FA content increased. A notable reduction in wear track width was observed (Figure 9), suggesting improved resistance to wear with increasing FA reinforcement (Othman et al., 2018). The promising performance of FA and QD in electroplated coatings underscores its viability for broader coating technologies, including anodic oxide coating. Moreover, the use of industrial waste helps divert significant volumes of non-biodegradable material from landfills and reduces the need for extraction of virgin raw materials, thereby lowering the carbon footprint of manufacturing processes. Given these benefits, industrial waste materials hold enormous promise to move beyond niche applications and be adopted more widely and strategically in surface coating systems, particularly as industries seek cost-effective, scalable, and environmentally responsible alternatives to commercial raw materials.

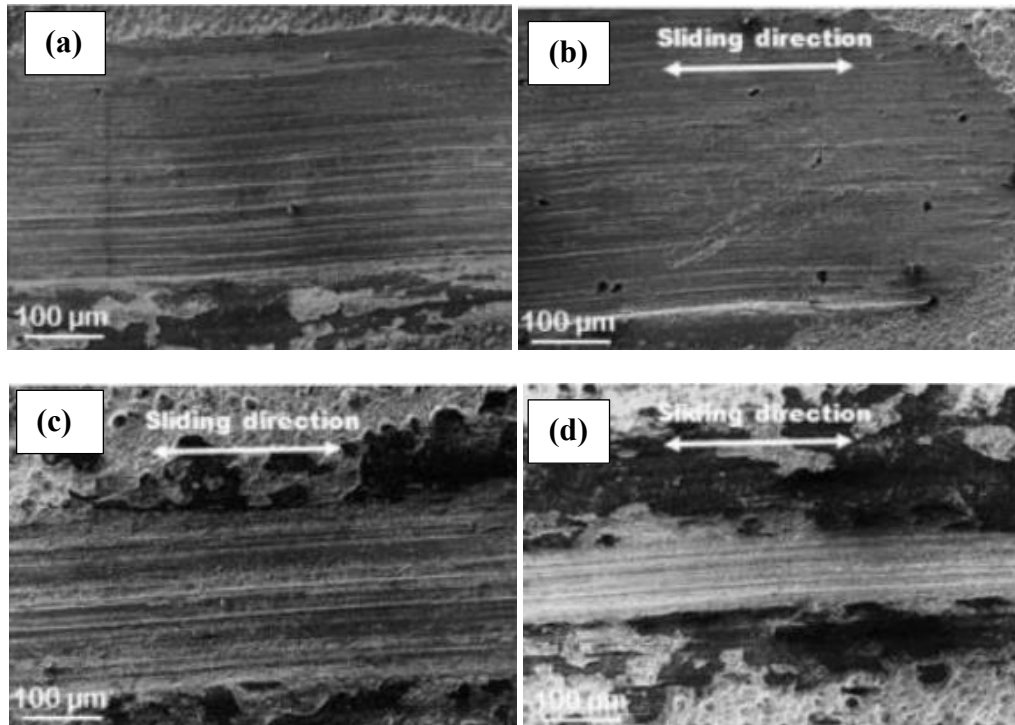


Figure 9: SEM morphology of wear track of the Ni-FA composite coatings, (a) without FA, (b) 10 g/L FA, (c) 50 g/L FA and (d) 90 g/L FA (Othman et al., 2018).

Overall, the strategic incorporation of reinforcement particles, particularly, industrial waste into the anodic oxide coatings offers a dual benefit: enhanced mechanical properties and environmental sustainability. These reinforcement particles play a critical role in strengthening the coating by minimizing porosity, preventing microcrack propagation, and improving resistance to plastic deformation and wear under tribological stress. This makes industrial waste-reinforced anodic oxide coatings particularly well-suited for high-performance applications involving repeated sliding contact, such as in the automotive, aerospace, and mechanical engineering sectors. With growing industrial demand for durable, eco-friendly surface technologies, the valorization of industrial waste in functional coatings represents a compelling and scalable pathway for the next generation of sustainable materials.

4.0 FA AND QD WASTE GENERATED FROM INDUSTRIES AND THEIR BROADER APPLICATIONS

4.1 Construction (Concrete) Industries

The potential of industrial waste materials such as FA and QD extends far beyond surface coatings, with their successful integration already well-established in industries including construction (concrete) industries, and composite material development (Ahmaruzzaman et al., 2009; Akhtar et al., 2018; Taiwo et al., 2022; Rajput et al., 2022; Salini et al., 2023). Over recent decades, FA has emerged as a promising supplementary cementitious material in the construction

sector, particularly in the production of sustainable concrete and geopolymer binders. Owing to its pozzolanic properties, FA enhances both the fresh and hardened properties of concrete (Bendapudi et al., 2011; Marthong et al., 2012). The reactive silica in FA interacts with calcium hydroxide from cement hydration to form additional calcium silicate hydrate (C-S-H), improving long-term strength and durability (Calabria-Holley et al., 2015; Kole et al., 2024). FA also contributes to lower heat of hydration, thereby reducing thermal cracking risks in mass concrete applications (Zhao et al., 2019; Do et al., 2020; De Matos et al., 2020). Its incorporation improves workability, reduces bleeding, and decreases chloride ion permeability, resulting in concrete with superior resistance to aggressive environmental conditions (Chindaprasirt et al., 2020; Wang et al., 2020). FA is typically used in replacement levels ranging from 15–35 wt% (Bhatty et al., 2006; Dhadse et al., 2008; Siddique et al., 2011; Sathawane et al., 2013; Baite et al., 2016), with some specialized applications, such as autoclaved aerated concrete and pavement concrete, allowing up to 70–80 wt% substitution (Wang et al., 2014; Marthong et al., 2012). While high replacement levels may slightly delay early strength development, optimized mix designs have shown that up to 45% FA can be used effectively in structural concrete without compromising performance (McCarthy et al., 2005; Elmrabet et al., 2019). This not only enhances material efficiency but also significantly reduces production costs and environmental impact.

Similarly, the use of QD as a partial or full replacement for fine aggregates in concrete has gained significant attention due to its favorable properties and sustainability benefits (Bahoria et al., 2014; Gautam et al., 2017; Sinha et al., 2017; Sundaralingam et al., 2022). Characterized by its angular (as shown in Figure 4), sharp-edged particles and high SiO₂ content, QD enhances mechanical interlocking within the cementitious matrix, resulting in improved compressive strength and elastic modulus (Pilegis et al., 2014; Zhao et al., 2020; Braimah et al., 2024; Shagwira et al., 2024). Studies have shown that concrete incorporating QD enhanced durability in aggressive environments (Venkatakrishnaiah et al., 2013). The available literature recommends the QD is generally used by 30-75% by mass of total cementitious matter, highlighting improvements in strength and durability, especially under acid and sulphate exposure, with compressive strength increases of up to 19.2% and tensile strength by 21.4% (Lohani et al., 2012; Balamurugan et al., 2013; Sukesh et al., 2013; Sureshchandra et al., 2014; Malik et al., 2015). However, the finer particle size and increased surface area of QD can reduce workability, necessitating the use of superplasticizers or the incorporation of FA to mitigate water absorption and improve mix rheology (Robert et al., 2018; Xu et al., 2025). Previous studies revealed that the combined use of QD and FA not only maintains or enhances mechanical performance but also addresses environmental concerns by diverting waste from landfills (Prahallada et al., 2013; Devi et al., 2015; Mukesh et al., 2021). For instance, mixes with 10% FA and 30–50% QD substitution demonstrated satisfactory mechanical properties and improved sustainability (Dehwah et al., 2012; Charkha et al., 2013). Overall, the use of FA and QD in concrete production is a viable and eco-efficient alternative to natural sand, aligning with the goals of resource conservation and sustainable construction practices.

4.2 Composites (Bulk)

In composites (metal matrix composites/polymer matrix composites), FA and QD serve as cost-effective reinforcement fillers that improve mechanical, thermal, and tribological properties. FA based-matrix composites have shown enhanced specific strength, hardness, and wear resistance, making them attractive for various applications in automotive components (brake lining), construction panels (building panel), and aerospace parts (fuselage panels) (Škvára et al.,

2005; Mohanty et al., 2007; Vivekananthan et al., 2011; Deshmukh et al., 2017; Yıldırım et al., 2019). While QD, due to its siliceous nature and angular morphology, has also been employed in polymer composites, where it improves hardness, high value of Charpy impact strength, and easy to process (Ramesh et al., 2014; Shagwira et al., 2024). These advances underscore the multi-sectoral applicability of industrial waste, supporting a systems-level approach to sustainability where waste (by-products) from one industry can become raw materials for another.

Previous studies have investigated the influence of incorporating FA particles into composites, and their subsequent impact on the tribological properties of these materials (Yoele et al., 2014; Sambyal et al., 2015; Zhu et al., 2017; Wang et al., 2022). Surappa et al. study investigated the impact of incorporating different weight percentages of FA particles into fabricated aluminum alloy composites and examined the resulting wear behavior (Surappa et al., 2008). The worn surfaces of the unreinforced aluminum alloy composite exhibited excessive ploughing (Figure 10), leading to higher wear loss. In contrast, the grooves on the worn surfaces of the reinforced aluminum alloy composites with a higher addition of FA filler were shallower, indicating improved wear resistance, where FA particles act as load-bearing constituents (Rao et al., 2018; Kumar et al., 2020). Moreover, the incorporation of up to 10 wt% FA content in aluminium alloy composites led to a reduction in wear loss, demonstrating superior wear performance compared to the base aluminium alloy. As shown in Figure 11, the worn surface of the aluminium matrix exhibited the presence of deep grooves, which may have contributed to the increased wear loss. The authors (Shaikh et al., 2018) suggested that the improved performance was also attributed to the better interfacial bonding between the aluminium matrix and the hard FA particles, which provide increased resistance to plastic deformation during wear process.

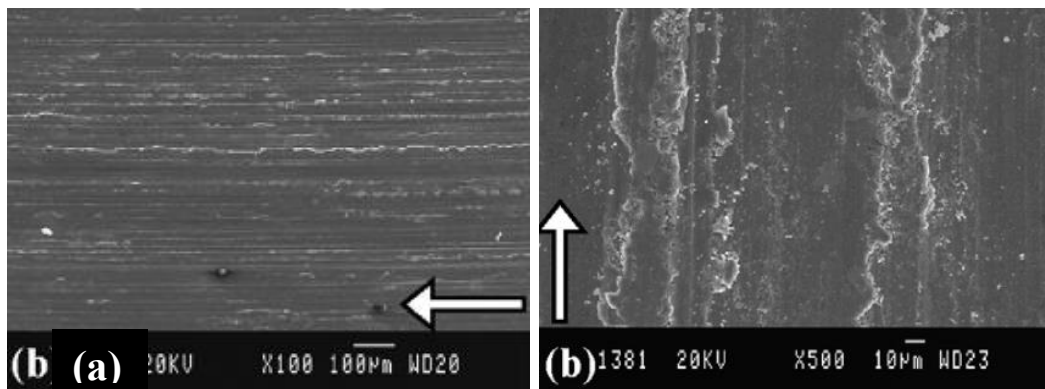


Figure 10: SEM micrograph of worn surface for (a) bare A356 Al alloy, and (b) composites with 12 vol. % FA (Surappa et al., 2008).

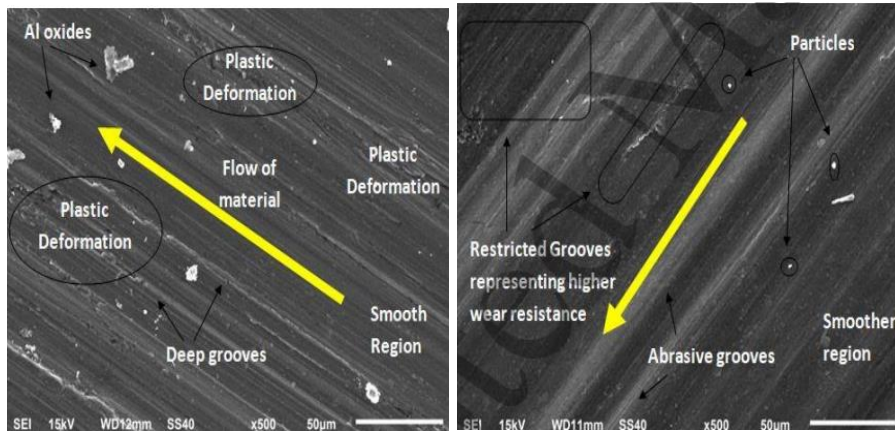


Figure 11: SEM image of worn surface for (a) Al only, and (b) Al-SiC-FA specimens (Shaikh et al., 2018).

The impact of QD particles on the tribological properties and performance of composite materials has been extensively studied. The mechanical and tribological performance of AlMg-Si alloy matrix composites reinforced with 8 wt% of combined QD and SiC in varying proportions revealed that QD serves as a viable partial substitute for conventional ceramic reinforcements (Ramesh et al., 2014; Taiwo et al., 2022). Mineralogical analysis identified quartz (SiO_2) as the primary constituents of QD. Incorporation of QD led to a slight reduction in composite density and demonstrated excellent wettability with aluminium, as evidenced by the low porosity levels. Notably, the addition of QD significantly enhanced the fracture toughness and strain to failure, suggesting improved damage tolerance (Aleneme et al., 2018; Gautam et al., 2023). Although the tensile and specific strengths displayed minor fluctuations with increasing QD, they remained within an acceptable range. Abrasive wear was identified as the dominant wear mechanism, confirming the suitability of these hybrid composites for applications where improved fracture resistance and acceptable wear performance are critical, all while benefiting from the cost and sustainability advantages offered by QD.

5.0 ENVIRONMENTAL AND ECONOMIC IMPACT OF UTILIZING INDUSTRIAL WASTE

5.1 CO_2 Reduction Potential

The integration of industrial waste materials (FA and QD) into anodic oxide coatings offers considerable potential to reduce CO_2 emissions across the materials value chain. Commercial ceramic reinforcements particles such as aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), silicon carbide (SiC), and zirconium dioxide (ZrO_2) are widely used in surface engineering. However, their production involves high-temperature synthesis routes, typically exceeding 1000°C , and often includes energy-intensive purification and sintering processes (Kim et al., 2002; Levashov et al., 2017). These manufacturing steps consume substantial amounts of energy, predominantly from fossil fuel which contributes significantly to global greenhouse gas (GHG) emissions. For instance, the production of one tonne of synthetic Al_2O_3 can release over 1.5 tonnes of CO_2 , while producing one tonne of primary aluminum can emit up to 11.5 tonnes of CO_2 , depending on the energy source used (Park et al., 2015; Li et al., 2022; Zawrah et al., 2023; Wang et al., 2024).

Consequently, the environmental footprint of commercial ceramic particles remains a concern, particularly in the context of sustainable development and carbon reduction targets. In contrast, FA and QD are pre-existing industrial waste with negligible embodied carbon, as they do not require primary extraction or high-temperature processing. Their use diverts waste from landfills, reduces emissions associated with material production and disposal, and supports net-zero and circular economy goals (Lee et al., 2017; Dal Pozzo et al., 2023). When applied in surface coatings, the incorporation of FA and QD contributes to carbon footprint reduction not only at the material production stage but also during product use by extending service life and reducing maintenance frequency (Mat Tahir et al., 2022; Yap et al., 2020).

5.2 Cost Benefit Compared to Commercial Materials

From an economic perspective, the substitution of commercial ceramics particles with industrial waste offers substantial cost-saving opportunities. High-performance ceramic powders such as Al_2O_3 or SiO_2 are not only expensive (due to complex processing) to produce but also subject to price volatility, impacting the scalability of advanced coating systems (Torabmostaedi, et al., 2013; Ambaryan et al., 2018; Vlasov et al., 2018; Oguntuyi et al., 2023). On the other hand, FA and QD are readily available at low or negligible cost, often requiring only basic pre-treatment steps such as drying, grinding, or sieving before use. This significantly reduces the raw material cost component, which can account for up to 50% of the total coating cost in some applications. Furthermore, anodic oxide coatings reinforced with FA and QD have shown comparable or improved functional performance in terms of hardness, wear resistance, and tribological stability, leading to a favorable performance-to-cost ratio. This makes industrial waste-based anodic oxide coatings especially attractive for cost-sensitive industries such as automotive, construction, agriculture, and infrastructure, where material affordability and lifecycle performance are both crucial (Firat et al., 2012; Cohen et al., 2019; Temuujin et al., 2019; Gopalakrishnan et al., 2020). When scaled up, these cost benefits extend to supply chain savings, reduced waste management fees, and alignment with green procurement policies, offering strategic advantages for manufacturers pursuing sustainable innovation.

6.0 RESEARCH GAP FOR FUTURE WORK

This review has clearly demonstrated that the incorporation of FA and QD into anodic oxide coatings can significantly enhance their mechanical properties and tribological performance. However, a notable research gap remains in assessing the corrosion resistance of these optimized anodic oxide coatings, which is essential for applications where Al alloys are exposed to both mechanical and corrosive stresses. Future work should address this by conducting comprehensive electrochemical analyses, including potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), to evaluate protective capabilities of the coatings in aggressive environments. This will enable a holistic understanding of their performance and ensure suitability for demanding sectors such as automotive, aerospace, and marine industries.

Another important research direction is to determine the thermal operating limits of these industrial waste-reinforced anodic oxide coatings. Evaluating both the maximum and minimum service temperatures using high temperature tribological testing and thermal analysis techniques would establish operational boundaries of the coatings. Such data will be vital for expanding their application into temperature-sensitive industries, including aerospace, automotive, and energy

sectors, where stability under fluctuating or extreme thermal conditions is as critical as mechanical durability.

CONCLUSIONS

This review emphasizes the growing potential of utilizing industrial waste materials, particularly FA and QD, as sustainable reinforcements in anodic oxide coatings, with a particular focus on enhancing mechanical properties and tribological performance. The incorporation of these industrial waste-derived particles into anodic oxide coatings has demonstrated substantial improvements in performance, including an increase in surface hardness of up to 116.9%, a reduction in wear rate of up to 65.21%, and a decrease in the coefficient of friction by up to 13.2% compared to unreinforced anodic oxide coatings. These significant enhancements are attributed to the favorable physicochemical properties of the industrial waste-derived particles, including fine particle size, spherical and angular morphologies, and a multiple composition (rich in silica and alumina), which facilitate effective pore filling, strong interfacial bonding, and improve surface quality (reduce porosity). Furthermore, the presence of quartz and mullite phase structures also contributes to high hardness and thermal stability. Such synergistic effects collectively address the key limitations of unreinforced (conventional) anodic oxide coatings.

Beyond performance gains, the use of FA and QD aligns strongly with sustainability goals, offering a dual benefit: the reduction of CO₂ emissions associated with the production and disposal of commercial ceramic materials, and the valorization of non-hazardous industrial waste. These materials are low-cost, widely available, and require minimal processing, making them ideal candidates for advancing circular economy practices and low-carbon manufacturing in surface engineering.

Moving forward, realizing the full potential of industrial waste-reinforced anodic oxide coatings will require interdisciplinary collaboration across materials science, surface engineering, and environmental technology. Key areas for future research include conducting long-term durability assessments and scaling up processes for industrial application. Furthermore, the integration of industrial waste particles, coupled with technology-economic evaluation, will be essential for transitioning these lab-scale innovations into commercially viable, environmentally responsible coating technologies. In conclusion, the use of industrial waste in surface coating represents a promising pathway toward next-generation functional coatings that are both high-performance and environmentally sustainable. With continued innovation and cross-sector engagement, these materials can play a transformative role in reducing industrial footprints and advancing global net-zero targets.

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