ENT9099ME10 - Aluminium Dross as a Cost-Effective Functional Filler for Sustainable Material Design and Development

Principal Investigator

Prof. Farrukh Hafeez	farrukh.hafeez@polytechnic.bh
Polytechnic ID: 12011258	**Department/School**: Engineering

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Company Endorsement	TAHA International
Industry mentor	Sabine Muller, Consultant, sabine@tahacopr.com, tel.: +97338841309

Background of the problem

Aluminium dross is a major industrial waste generated during aluminium production, processing, and recycling. It is estimated that 30–50 kg of dross is produced per tonne of primary aluminium and 100 to 150 kg per tonne during secondary aluminium recycling (Liu et al., 2024). Although policymakers and aluminium producers recognise the strategic importance of dross recycling, large quantities remain underutilised, with landfilling still a common disposal route. While extensive research has focused on chemical recovery of aluminium and alumina from dross, comparatively fewer studies have examined its potential as a functional filler or reinforcement in advanced material systemsMailar et al. (2016) investigated the behaviour of concrete incorporating recycled aluminium dross under hot weather conditions. The study did not evaluate the mechanical performance of the material after exposure to hot weather conditions, leaving a gap in understanding temperature dependent behaviour. Dastan Diznab et al. (2026) evaluated the influence of aluminium dross on mortar exposed to sulfuric acid. Beyond cementitious systems, several studies have explored aluminium dross in polymer and composite materials. Agunsoye et al. (2014) demonstrated that incorporating particulate dross into epoxy resin significantly improved thermal stability and wear resistance. Samat et al. (2017) blended aluminium dross with polypropylene and observed enhanced thermal and flame resistance, along with increased Young's modulus. However, high dross contents (>40 wt.%) reduced ductility. Existing studies are fragmented, often limited to specific applications, and do not comprehensively address dispersion behaviour, interfacial performance, temperature-dependent mechanical properties, or multiscale modelling of dross-filled composites. These gaps underscore the need for a systematic and holistic investigation, as outlined in the aims and objectives of this project.

List of publications related to the field

1. To identify the optimal proportion of aluminium dross required to achieve enhanced mechanical, thermal, and functional performance in composite systems.
2. To investigate the dispersion characteristics of aluminium dross within matrix materials and evaluate its interfacial bonding mechanisms.
3. To assess the mechanical, thermal and durability performance of composites incorporating aluminium dross as a filler.
4. To evaluate the mechanical performance of aluminium-dross-filled material at different temperatures in order to understand their suitability under local climatic conditions.
5. To design and optimize sustainable composite materials that effectively utilize aluminium dross while reducing reliance on virgin raw materials.
6. To characterize the physical, chemical, and microstructural properties of aluminium dross.

Research Objectives and Expected Outcomes

Aim & Objectives:

To develop and optimize innovative composite materials by upcycling aluminium dross as a functional constituent, supporting sustainable and circular material design.

Expected Outcomes:

- Validated potential of aluminium dross as a functional filler.
- Optimised material formulations.
- Temperature-dependent performance data.
- Improved understanding of microstructure to property relationships.
- Sustainable material prototypes.
- Contribution to Bahrain’s sustainability and circular economy goals.
- Capacity building and knowledge advancement.

Research Design & Methodology

The research methodology for this project is grounded in experimental, analytical, and materials engineering techniques. The approach integrates literature-based inquiry, material design, manufacturing, microstructural characterization, and performance evaluation. A high level breakdown of the major methodological components is provided below.
Literature Review: A comprehensive review of existing knowledge will be conducted to establish the scientific and technical foundation for the study. This includes critical evaluation of state-of-the-art material design strategies, particularly the use of functional constituents and fillers for

performance enhancement. Identification of knowledge gaps, limitations in current approaches, and opportunities for innovation in hybrid composite development.

Material Design and Constituent Engineering: This phase focuses on the conceptual and technical development of the hybrid material system. Key activities include Selection and optimization of constituent ratios, including aluminium matrix, fillers, and functional additives. Engineering of dispersion strategies to ensure uniform distribution of fillers and minimize agglomeration.

Manufacturing and Processing Methods: The hybrid material will be fabricated using controlled and repeatable processing techniques. This includes optimization of processing parameters such as temperature, mixing speed, compaction pressure, and cooling rate.

Implementation of quality-control measures to ensure consistency across batches.

Documentation of processing-structure relationships to support later analysis.

Microstructural Evaluation: Microstructural characterization will be performed to establish the link between material morphology, constituent distribution, and resulting properties. SEM, DMA and optical microscopy to be used to assess phase distribution and interface behaviour. The objective is to correlate microstructural features with mechanical and environmental performance.

Experimental Testing Programme: A structured experimental programme will be conducted to evaluate the performance of the developed hybrid material. This includes Mechanical testing (e.g., tensile, compression, hardness, impact) and thermo-mechanical testing where relevant. Additionally, Controlled variation of environmental factors such as humidity, temperature, and exposure conditions to understand operational robustness. The results will be used to identify key performance drivers and optimize the material formulation.

Environmental and Operational Performance Evaluation: This section assesses how the hybrid material performs under realistic service conditions. Activities includes testing for corrosion resistance, oxidation behavior, and environmental degradation, particularly relevant for aluminum-based systems.

Integrated Performance Assessment: The final stage synthesizes findings from all previous phases to provide a holistic evaluation of the hybrid material system. This includes Integration of microstructural, mechanical, and environmental data to establish structure, property, performance relationships.

Significance and potential impact of research in Bahrain

This research project investigates the utilization of aluminium dross an industrial waste generated during aluminium production as a functional filler for innovative material design. By transforming an industrial waste stream into a value added resource, the study contributes directly to UN Sustainable Development Goals through waste upcycling, resource efficiency, and circular economy practices.

A comprehensive understanding of the role of aluminium dross in composite systems requires addressing several key aspects: identifying the optimal filler content, examining dispersion behavior, evaluating interfacial interactions, and assessing the overall performance of dross filled materials. This project systematically explores these dimensions to establish the scientific basis for its effective integration.

This work offers significant potential across multiple material classes, enabling performance enhancement and property tailoring in diverse composite systems. It opens pathways for the incorporation of aluminium dross in concrete, cementitious composites, polymer matrices, and fibrous composites, thereby broadening its applicability in structural, thermal, and refractory applications.

The study holds direct relevance for environmental sustainability, industrial innovation, and economic efficiency. By advancing material design strategies that rely on waste derived fillers, the project supports reduced carbon emissions, improved waste management, and enhanced circular economy performance.

This project contributes to the scientific and academic knowledge by understanding of material behaviour through microstructural analysis, property characterization, and performance evaluation.

Overall, this research strengthens the foundation for sustainable material innovation and demonstrates how industrial waste can be transformed into a high-value engineering resource.

Alignment with Bahrain's national research strategy

This research proposal directly aligns with the Bahrain National Policy, requirements of the industry and benefits to the society. At the national policy level, the project directly supports three strategic pillars of Bahrain's Economic Vision 2030: diversification of the industrial economy beyond hydrocarbon dependence, development of a circular economy in the manufacturing and construction sectors, and enhancement of environmental sustainability. The project serves as a proof of concept for the broader principle that Bahrain's industrial by products can be productively reintegrated into the local economy rather than exported as waste or consigned to local waste disposal.

Transforming aluminium dross into a functional filler supports Bahrain's national sustainability agenda by keeping industrial by products within the economic cycle. This aligns with the country's move toward resource efficiency, waste disposal, and UN SDGs. This project directly aligns with multiple UNSD goals including Sustainable cities and communities, Responsible consumption and production, Life on land and Quality education.

By studying the performance of dross-based materials under Bahrain's hot climate, the project supports the creation of materials better suited to local environmental conditions. This can improve durability, reduce maintenance costs, and enhance infrastructure resilience.

The project opens pathways for new products e.g. composites, fillers, refractory materials, thus creating opportunities for SMEs, material manufacturers, and recycling companies. This supports Bahrain's economic diversification goals under Vision 2030.

The project builds scientific expertise in materials engineering, multiphysics modelling, and sustainable design within Bahrain's academic and industrial sectors. It supports capacity building for students, researchers, and engineers, strengthening the national innovation ecosystem.