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FROM WASTE TO RESOURCE: IMPLEMENTING SPENT GARNET (SG) AS A PARTIAL FINE AGGREGATE IN CEMENT-BASED MATERIALS - TECHNICAL, LEGAL AND COMMERCIAL PERSPECTIVES

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Abstract

The growing demand for natural aggregates and stricter environmental regulations are driving the construction sector toward the valorisation of industrial by-products. This study investigates the technological transfer potential of Garnet sand waste (SG) as a partial substitute for natural fine aggregates in cement-based building materials, including mortars and concrete. Experimental results at laboratory and preliminary pilot scale demonstrate that controlled replacement levels of SG can achieve comparable or improved fresh and hardened properties relative to reference mixes, while meeting durability and performance requirements. Beyond technical validation, the paper examines the legislative framework governing waste reuse in construction, with particular attention to aggregate standards, waste-to-product transition, and conformity assessment procedures. Finally, commercial and market aspects are addressed, identifying barriers and drivers for industrial uptake, stakeholder acceptance, and potential business models within a circular economy context. The results provide an integrated pathway proposal for transforming Spent Garnet (SG) sand waste from an industrial residue into a viable construction resource, supporting sustainable material innovation and market implementation.

Key words*: cement-based materials, circular economy, fine aggregate substitution, market adoption, spent garnet (SG), sustainable construction, technology transfer, waste regulation.*

INTRODUCTION

The construction industry remains one of the largest consumers of natural resources worldwide, particularly mineral aggregates used in concrete and mortar production. The growing demand for infrastructure and urban development has significantly increased the extraction of natural aggregates, generating environmental concerns related to landscape degradation, energy consumption, and greenhouse gas emissions (Corbu et al., 2014; Mattra et al., 2025). At the same time, industrial activities produce substantial quantities of mineral waste streams that are often disposed of in landfills, despite their potential reuse as secondary raw materials.

Within this context, the circular economy paradigm promotes the transformation of industrial by-products and waste into valuable resources (Potting et al., 2017; Morseletto, 2020). By closing material loops and reducing dependency on virgin raw materials, circular economy strategies can contribute to both environmental protection and resource efficiency in the construction sector. The reuse of mineral residues in cement-based materials has therefore gained increasing attention in recent years.

One such industrial residue is spent garnet sand generated from abrasive waterjet (AWJ) cutting operations. Garnets are widely used as abrasives medium due to their high hardness, chemical stability, and cutting efficiency (Perianu et al., 2014; 2017). However, after repeated use in AWJ processes, the material becomes contaminated with fine particles and loses its suitability for further abrasive applications. As a result, large quantities of spent garnet (SG) are

generated globally and are commonly classified as industrial waste, leading to disposal costs and environmental impacts (Baera et al., 2026a).

Previous studies have demonstrated that garnet residues generated by AWJ processes (AWJ-SG), with suitable granulometry and mineralogical composition, can partially replace natural aggregates in cement-based materials without compromising mechanical performance. AWJ spent garnets (AWJ-SGs) show considerable potential for application in cement-based materials (Ab Kadir et al., 2019; Lim et al., 2020; Budiea et al., 2021; Jamaludin et al., 2021; Kanta et al., 2022) as well as in alkali-activated concrete (Muttashar et al., 2017; 2018a, 2018b; Huseien et al., 2019), mortars (Kunchariyakun et al., 2020; Baera et al., 2025; 2026a), plasters, fibre-reinforced composites, and other construction materials.

Nevertheless, the transition from laboratory - scale investigations to practical implementation remains limited. In many cases, technological feasibility is demonstrated but the broader aspects required for industrial adoption - such as regulatory compliance, certification procedures, and market acceptance are insufficiently addressed (Baera et al., 2026a). In this context, the present study investigates the potential valorisation of single cycle AWJ spent garnets as partial substitute for natural fine aggregates in cement-based materials, including mortars and concrete. Beyond the technical evaluation of substitution viability, the study also addresses complementary dimensions, including technological transfer challenges, the legislative framework governing waste reuse in construction and product certification, and broader commercial and market-related considerations, all of which influence the practical implementation of circular economy principles. By combining these dimensions, the paper proposes an integrated pathway for transforming spent garnet from an industrial residue into a viable construction resource, supporting sustainable material innovation within a circular economy framework.

CIRCULAR ECONOMY (CE) CONTEXT FOR AWJ SPENT GARNET (AWJ-SG)

The transition toward a circular economy requires the development of strategies that reduce waste generation and promote the efficient use of resources across industrial sectors. The integration of sustainable materials and innovative techniques in civil engineering contributes to environmental protection while enhancing resource efficiency and structural reliability, thereby supporting the transition toward more sustainable construction practices (Olinic et al., 2024). In the construction industry, one of the most promising approaches involves the integration of secondary materials derived from industrial processes into building materials. Such practices can simultaneously reduce waste disposal and decrease the consumption of natural aggregates.

Abrasive waterjet (AWJ) cutting is widely applied in manufacturing industries for the precise cutting of metals, ceramics, composites, and stone materials (Perianu et al., 2023). Garnet is commonly used as the abrasive medium due to its favourable mechanical and chemical properties (Chassé et al., 2018). During the AWJ process, garnet particles progressively fracture and become mixed with removed material and fine debris. In some cases, SG waste can be recycled and reused for its original application as AWJ abrasive, although few initiatives have focused on this type of material recovery. In most cases, after one AWJ use the resulting SG material is discharged as spent garnet waste.

From a material flow perspective, the lifecycle of garnet in AWJ operations typically includes four stages: extraction of natural garnet, use as an abrasive medium, generation of spent garnet waste, and final disposal. In many industrial facilities, the spent material is collected as sludge or dried sand and transported to landfill sites. This linear disposal pathway results in both environmental impacts and additional operational costs. Within a circular economy framework, spent garnet can be considered a secondary mineral resource. Several potential valorisation routes have been explored, including reuse as abrasive media after processing, use in sandblasting operations, and incorporation into construction materials. Among these options, the use of AWJ-SG as a fine aggregate substitute in cement-based materials presents significant potential, considering its proven suitability for integration and the large volumes of aggregates required in the construction sector. The integration of spent

garnets into mortar and concrete production can therefore represent a form of industrial symbiosis, offering a dual advantage, as illustrated in Figure 1: first, it diverts waste from disposal pathways, generating positive environmental and economic impacts from a waste management perspective. Second, it partially replaces natural aggregates, thereby reducing the pressure on natural resource extraction.

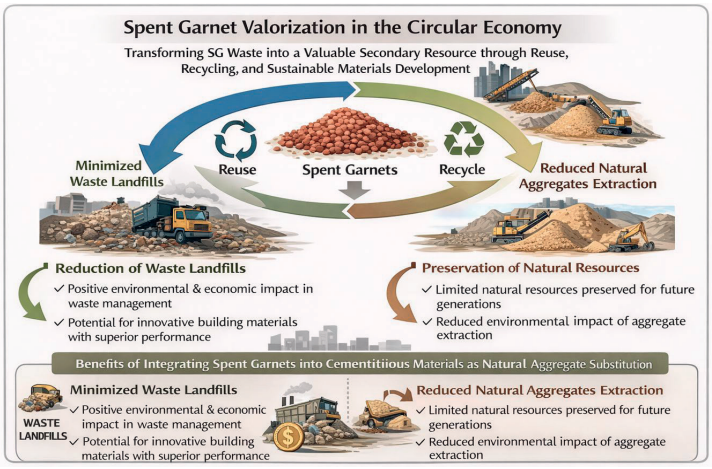


Figure 1. Circular Economy Framework for Spent Garnet Waste Valorization in Cementitious Materials (AI-generated image)

In Romania, the valorization of AWJ-SG waste in construction materials and products through the innovative substitution of fine aggregates was investigated within one of the research axes of project PN 23 35 04 01 (Figure 2), entitled "Development of innovative engineering solutions for eco-intelligent construction products through the efficient valorization of additions generated by local industries".

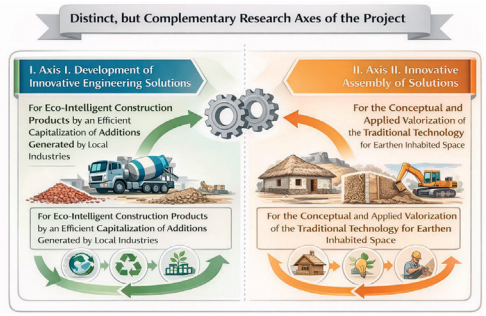


Figure 2. Schematic representation of the research axes of project PN 23 35 04 01 (AI-generated image)

The project is part of the Nucleu Programme under the National Research, Development and Innovation Plan 2022-2027 (ECODIGICONS), funded by the Romanian Ministry of Research, Innovation and Digitalization, and is aligned with European Union objectives and national strategic frameworks such as Romanian National Strategy on the Circular Economy (SNEC, 2022) and the National Strategy for Research, Innovation and Smart Specialization (SNCISI 2022-2027, 2022).

The project's main goal is to facilitate technological transfer and enable the practical implementation of the developed materials, products, and technologies through sustained collaboration among key stakeholders, including academia and research institutions, entrepreneurs, industrial users and end-consumers, suppliers, and social, economic, and political actors, as well as local and central authorities.

MATERIALS AND METHODS

The procedure-based transition of abrasive waterjet spent garnet (AWJ-SG) from industrial waste to a construction resource is conceptualized through *a three-layer circular economy framework*, represented by a *technology-transfer diagram structured around three complementary layers* (Figure 3):

(i) *Technical layer*, addressing material characterisation, mix design optimisation, prototype validation, pilot-scale trials, and the transition from laboratory research to field implementation;
(ii) *Regulatory layer*, covering compliance with relevant standards, waste legislation, and the procedures required for product certification and conformity assessment; and
(iii) *Commercial layer*, focusing on supply-chain integration, stakeholder engagement, and the market adoption of AWJ-SG-based construction materials.

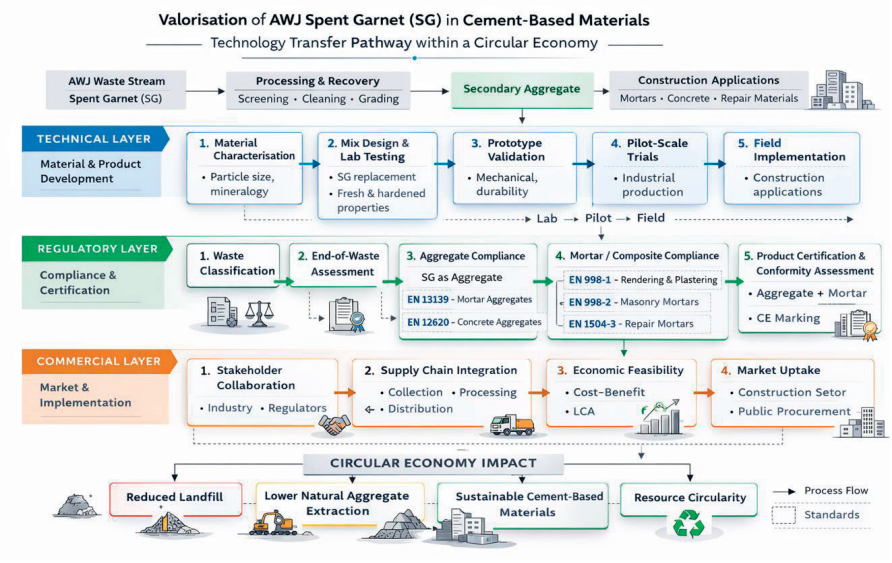


Figure 3. Spent Garnet Waste Valorization in Cementitious Materials:
Three-Layer Circular Economy Structure (AI-generated image)

The figure illustrates the transition of AWJ SG material from industrial residue to construction resource through three complementary implementation layers. The technical layer describes the progression from material characterization to field application. The regulatory layer distinguishes between compliance of SG as aggregate and compliance of the final mortar-based product, including relevant European standards for aggregates, rendering/plastering mortars, masonry mortars and repair mortars. The commercial layer captures the supply-chain and market conditions needed for industrial uptake. Together, these layers define the practical pathway for circular economy implementation of AWJ-SG in cement-based materials.

I. Technical Layer: SG as Fine Aggregate Substitute in Cement-Based Mortars

The technical implementation of abrasive waterjet spent garnet (AWJ-SG) as a secondary aggregate in cement-based mortars follows a progressive validation pathway that includes specific technical stages like *material characterization, mix design optimization, prototype validation and pilot-scale assessment* (Figure 4). The proposed methodological framework aims to verify the feasibility of transforming AWJ-SG from an industrial waste stream into a functional construction material within a CE context, while ensuring consistent performance and reproducibility of results.

Material Characterisation

The initial stage focuses on the *physical, chemical and mineralogical characterisation of AWJ-SG* in order to evaluate its suitability as a fine aggregate substitute in cement-based composites. Key parameters include particle size distribution (PSD), particle morphology, density and potential impurities resulting from the abrasive cutting process.

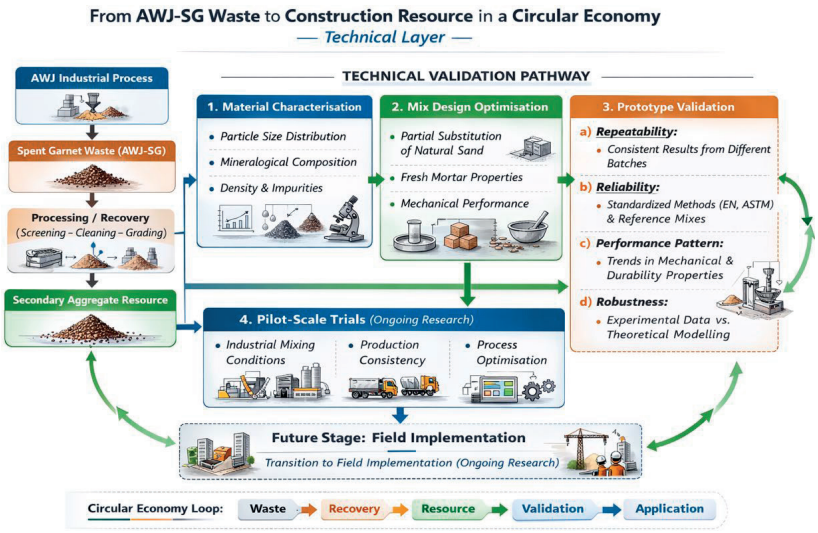


Figure 4. Circular economy pathway for valorisation of AWJ spent garnet (AWJ-SG) as a secondary aggregate: from waste generation to technical validation and pilot-scale implementation (AI-generated image)

These characteristics were analysed (Baera et al., 2026a) and identified the expected compatibility with the grading requirements of conventional mortar aggregates; also, the potential effects on fresh and hardened properties were also identified and discussed. Proper processing steps, such as screening and cleaning, were also considered to ensure consistent material quality before incorporation into mortar mixtures. market adoption of SG-based construction materials.

Mix Design Optimisation

To assess the feasibility of using spent garnets (SG) as a fine aggregate substitute, mortar mixtures were prepared with varying partial replacement levels (30% and 50%) of natural sand while maintaining acceptable aggregate grading. Conventional cement binders and typical water-to-binder ratios were used. Reference mixtures containing only natural aggregates were produced for comparison. SG was introduced by replacing a portion of the natural sand while keeping the binder content and overall mix proportions constant. This approach enabled evaluation of the influence of SG on fresh and hardened properties while minimizing the impact of other variables; the expected SG to cementitious matrix compatibility was identified (Baera et al., 2025; 2026a).

Prototype Validation

Prototype validation was conducted to confirm the feasibility and consistency of incorporating spent garnet (SG) as a partial fine aggregate substitute in cement-based mortars. The validation procedure was initiated and further developed (Baera et al., 2025; 2026a) to follow a structured methodology based on four general criteria. *Repeatability* was assessed by verifying that comparable performance results were obtained for successive SG batches collected at different times, both from the same and from different sources. *Reliability* was ensured through testing performed according to standardized procedures (e.g., EN and ASTM methods) and by comparing the results with those obtained from reference cement–sand control mixtures. *Performance pattern* was evaluated by analysing systematic trends in mechanical and durability properties as a function of SG substitution levels and the characteristics of the waste material. Finally, *robustness* was examined by correlating experimental observations with theoretical modelling in order to minimise the influence of uncontrolled experimental variability and confirm the consistency of the proposed material system.

The results (Baera et al., 2026a) are validating the SG mortar prototypes and the viability of the proposed integrating concept, at laboratory scale

and also are founding the technological transfer to the industry, ensuring the transitioning to pilot scale assessments.

Pilot-scale assessment

Pilot-scale assessment represents the next stage in the implementation pathway for the valorisation of AWJ spent garnet (AWJ-SG) as a secondary aggregate in cement-based mortars. This stage aims to verify the reproducibility of laboratory results under industrial mixing conditions, including *batching procedures, mixing energy, and material handling practices* typically encountered in mortar production facilities. Particular attention is given to *production consistency*, ensuring that the incorporation of AWJ-SG does not introduce variability in fresh or hardened properties across successive batches. Monitoring of parameters such as aggregate dosing, moisture control, and mixing duration is therefore required to maintain stable production quality. In parallel, process *optimisation measures* are being investigated, including adjustments to mixing sequences, particle grading control, and potential pre-treatment steps (e.g., screening or drying) to ensure uniform material behaviour at scale. These ongoing investigations aim to confirm that the performance trends observed in laboratory conditions can be reliably reproduced in industrial environments, thereby supporting the transition of AWJ-SG from experimental validation toward industrial implementation.

II. Regulatory and Legal Layer for AWJ-SG Waste-to-Product Transition

The regulatory layer establishes the legal and conformity framework required for the transition of AWJ spent garnet (AWJ-SG) from waste status to a construction resource. The corresponding regulatory validation pathway, illustrated in Figure 5, includes waste classification, evaluation of end-of-waste/by-product conditions, compliance with aggregate and mortar standards, and product certification in accordance with Regulation (EU) No. 305/2011.

Waste Classification

The first regulatory step involves the classification of abrasive waterjet spent garnet (AWJ-SG) within the waste management framework. In Romania, this process follows HG nr. 856/2002 regarding waste management records and the approval of the waste list, which is aligned with European waste legislation, particularly Commission Decision 2000/532/EC establishing the European List of Waste (LoW). Within this framework, AWJ spent garnet can be classified under code 12 01 17 - "waste blasting materials other than those mentioned in 12 01 16". *This classification establishes the regulatory basis for waste handling, traceability, and further evaluation of potential recovery or valorisation pathways*.

End-of-Waste/By-Product Assessment

Following waste identification, an end-of-waste or by-product assessment is required to determine whether AWJ-SG can transition from a waste material to a secondary resource suitable for construction applications. This evaluation considers criteria such as the intended use of the material, *compliance with technical specifications, absence of environmental or health risks, and the existence of a stable market demand*. Demonstrating that the processed material can be safely and consistently used as an aggregate substitute is essential for enabling its transition from waste status to a recoverable construction resource.

AWJ-SG Aggregate Compliance

Once the material is considered suitable for recovery, AWJ-SG must demonstrate technical compliance with relevant aggregate standards. For applications in cement-based mortars, the material must meet the requirements specified in EN 13139 - Aggregates for mortars, including particle size distribution, density, and cleanliness parameters. For potential applications in concrete, compliance with EN 12620 - Aggregates for concrete must also be assessed. These standards ensure that the recovered material meets the necessary physical and mechanical properties required for use as a construction aggregate.

Mortar/Composite Compliance

In addition to aggregate-level compliance, the performance of the final cement-based composite containing AWJ-SG must satisfy the relevant mortar standards, depending on the intended application.

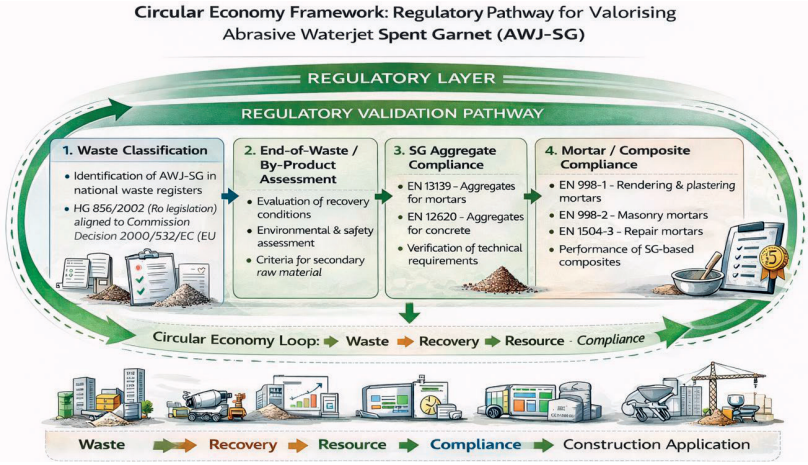


Figure 5. Circular economy pathway of AWJ-SG Waste-to-Product transition (as a secondary aggregate): Regulatory and Legal layer (AI-generated image)

Rendering and plastering mortars must comply with EN 998-1, masonry mortars with EN 998-2, and repair mortars used for concrete structures with EN 1504-3. Compliance with these standards requires the evaluation of mechanical strength, durability, and other performance characteristics to ensure that the incorporation of SG does not negatively affect the functional behaviour of the mortar.

Product Certification & Conformity Assessment

The final regulatory step involves product certification and conformity assessment, ensuring that both the aggregate component and the final mortar-based product meet the requirements for placing construction products on the market. This process is carried out in accordance with Regulation (EU) No. 305/2011 (Construction Products Regulation – CPR) and may involve testing, factory production control, and conformity verification procedures. Certification therefore addresses both aggregate compliance and mortar/composite performance, enabling the resulting product to be marketed as a compliant construction material within the European regulatory framework.

III. Commercial Layer for AWJ-SG Waste-to-Product Transition

After establishing the regulatory framework for the valorization of AWJ-SG, the focus moves to the commercial layer, which examines supply-chain organization, stakeholder engagement, business model development, and the conditions necessary for market adoption of SG-based construction materials (Figure 6).

Supply-Chain Integration

The commercial implementation of AWJ spent garnet (AWJ-SG) valorisation requires the integration of the material into existing construction material supply chains. This involves *establishing logistical connections between abrasive waterjet processing facilities, waste recovery operators, and construction material producers*. Efficient supply-chain integration ensures that SG can be collected, processed, and delivered in a consistent form suitable for use as a secondary aggregate in cement-based materials.

Stakeholder Engagement

Successful market implementation depends on the active involvement of key stakeholders, including AWJ operators, waste management companies, construction material manufacturers, regulatory authorities, and end users. Stakeholder engagement is essential for building trust in the technical performance and environmental safety of SG-based materials, as well as for facilitating knowledge exchange and promoting acceptance within the construction sector.

Supply-Chain Organisation

The development of a reliable supply chain structure *is necessary to ensure the consistent availability and quality of AWJ-SG*.

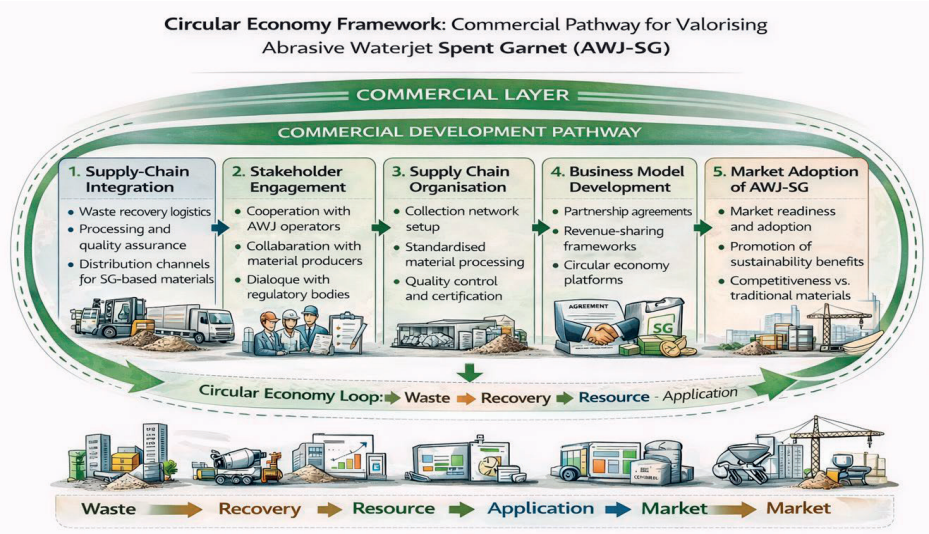


Figure 6. Circular economy pathway of AWJ-SG Waste-to-Product transition: Commercial layer (AI-generated image)

This includes the establishment of *standardized collection procedures, material processing operations, and quality control mechanisms* to guarantee that the recovered aggregate meets technical and regulatory requirements before entering the construction materials market.

Business Model Development

The valorisation of AWJ-SG also requires the identification of *sustainable business models* that balance economic feasibility with environmental benefits. Potential models may include partnerships between AWJ service providers and construction material producers, waste recovery agreements, or circular economy platforms that promote the reuse of industrial by-products. In addition, *social entrepreneurship initiatives* may represent a viable approach, particularly where waste recovery and material processing activities can generate local employment and support community-based circular economy practices. Such models combine environmental value creation with social impact, contributing to both resource efficiency and regional socio-economic development (Baera et al., 2026b) Overall, these approaches aim to reduce disposal costs while creating additional value from recovered materials.

Market Adoption of AWJ-SG-Based Construction Materials

The final stage involves the market uptake of construction materials incorporating AWJ-SG. This process depends on demonstrating *technical reliability, regulatory compliance, and economic competitiveness* compared to conventional materials. As confidence in the performance and sustainability benefits of SG-based mortars increases, their adoption may contribute to reducing the consumption of natural aggregates and supporting CE practices within the construction sector.

Together, the technical validation, regulatory compliance, and commercial integration layers form a coherent circular economy framework that enables the sustainable transition of AWJ spent garnet from an industrial waste stream to a viable construction resource.

RESULTS AND DISCUSSIONS

I. Technical Layer: SG as Fine Aggregate Substitute in Cement-Based Mortars

The results obtained from the experimental investigations confirm the technical feasibility of incorporating abrasive waterjet spent garnet (AWJ-SG) as a partial fine aggregate substitute in cement-based mortars. The evaluation followed the staged validation pathway described in the methodology section, including material characterisation, mix design optimisation, prototype validation, and preparation for pilot-scale assessment.

The *physical, chemical and mineralogical characterisation of AWJ-SG* performed in previous studies (Baera et al., 2026a) confirmed

via PSD determination, Scanning Electron Microscopy (SEM) analysis, X-Ray Diffraction (XRD) analysis and Fourier Transform Infrared Spectroscopy FTIR technique that the material exhibits properties compatible with the requirements of conventional mortar aggregates, that they are inert and safe for use in regular mixtures. The particle size distribution (PSD) of the processed SG fractions was found to fall within the grading range suitable for fine aggregates used in cement-based mortars. In addition, the angular particle morphology, typical of abrasive materials, may contribute to enhanced mechanical interlocking within the cementitious matrix. The density and mineralogical composition of the material were also consistent with the characteristics expected for silicate-based abrasive sands. Potential impurities associated with the cutting process are removed using the proposed specific procedure, which includes collection, screening and sorting, cleaning and verification, and storage operations, ensuring a stable and reproducible material suitable for mortar formulations.

Based on the material characterisation results, *the Mix Design Optimisation* stages led to mortar mixtures prepared using partial replacement levels of natural sand with AWJ-SG at 30% and 50%, while maintaining consistent binder content and water-to-binder ratios. The experimental results (Baera et al., 2026a) indicated that the incorporation of SG within these substitution ranges did not adversely affect the fresh properties of the mortars (visual aspect, consistency and fresh state density), while mechanical performance (compressive and flexural strength at early, regular and late ages) offered superior performance when compared to reference mixtures containing only natural aggregates. These observations confirm the compatibility between SG particles and the cementitious matrix, supporting findings reported in previous studies (Baera et al., 2025). The optimisation of the mix design therefore demonstrated that SG can be effectively integrated into mortar formulations without significant modifications to conventional mixture proportions.

The *prototype validation stage* aimed to verify the reproducibility and reliability of SG-based mortar formulations. Experimental testing carried out according to standardized methods (EN and ASTM procedures) confirmed that the incorporation of SG produces consistent performance trends across different batches of material. The validation procedure followed a structured framework based on four criteria: repeatability, reliability, performance pattern and robustness. Comparable results were obtained for SG batches collected from different sources and time periods, confirming the repeatability of the material behaviour. Reliability was ensured through the comparison of SG-based mixtures with conventional cement–sand reference mortars. Furthermore, systematic performance trends were observed with respect to SG substitution levels, while correlations between experimental results and theoretical expectations confirmed the robustness of the proposed material system. Overall, the results reported by Baera et al., (2026) validate the SG mortar prototypes at laboratory scale and demonstrate the technical viability of the proposed valorisation concept.

Following laboratory validation, the next stage *involves pilot-scale assessment*, aimed at verifying the reproducibility of the experimental results under industrial production conditions. This stage focuses on evaluating industrial mixing procedures, batching practices and material handling conditions typically encountered in mortar production facilities.

The current research phase developed a mixing procedure different from the standardized method (paddle mixer, rotational speed 140/280 rpm; revolutionary motion 61.5/123 rpm, according to EN 196-1). The objective was to create a simpler and more accessible manufacturing approach, better suited for technology transfer to industrial operators. The proposed technology involves mixing with a mortar mixer in a standard container (bucket/mixing vat) and includes the following steps: Step 1 - Dry mixing (natural sand + SG-AWJ addition); Step 2 - Dry mixing (aggregate + cement); Step 3 - Addition of water (and additive, if applicable); Step 4 - Visual inspection for proper consistency and absence of lumps.

The *critical characteristics* of standard AWJ-SG mortars required for calibrating the proposed technological transfer, as well as *the validation criteria*, are defined in the proposed ***Primary Validation Procedure***:

1 Properties in the fresh state: Visual appearance; Consistency; Bulk density (fresh state);
2. Properties in the hardened state: Bulk density (hardened state) and water absorption; Compressive strength (at 7 and 28 days); Flexural strength (at 7 and 28 days).

Validation criterion: Similar performance trends (a stable pattern) must be obtained, even if absolute values vary slightly between batches, within an acceptable margin of ±15%.

Ongoing study considers particular attention for ensuring production consistency, for preventing variability in fresh and hardened properties when AWJ-SG is incorporated into mortar formulations at larger scales. In parallel, process optimisation measures are being investigated, including adjustments to mixing sequences, aggregate grading control and potential pre-treatment operations such as additional screening or drying of the SG material. The successful scaling of these processes would support the *transition from experimental validation to industrial implementation*, enabling AWJ-SG to be integrated into cement-based materials as a secondary aggregate. From a circular economy perspective, this transition contributes to reducing landfill disposal of industrial abrasive waste while simultaneously lowering the demand for natural aggregate resources in the construction sector.

II. Regulatory and Legal Layer for AWJ-SG Waste-to-Product Transition

The regulatory assessment indicates that the valorisation of abrasive waterjet spent garnet (AWJ-SG) as a secondary aggregate in cement-based mortars can be supported by the existing European and national regulatory framework. This stage of the research focuses on identifying the legal conditions under which AWJ-SG can transition from an industrial waste stream to a construction resource, while ensuring compliance with applicable waste management legislation and construction product standards. The results presented here outline the proposed regulatory pathway, which will be further investigated and validated in subsequent stages of the research.

Waste Classification

The regulatory pathway begins with the identification of AWJ-SG within the waste management framework. In Romania, this process is governed by HG nr. 856/2002, which regulates waste management records and establishes the national waste list, aligned with the European List of Waste defined by Commission Decision 2000/532/EC. Under this classification system, AWJ spent garnet can be assigned to code 12 01 17 – waste blasting materials other than those specified in 12 01 16, providing the legal basis for its traceability and further evaluation for recovery.

End-of-Waste/By-Product Assessment

A key step in the regulatory transition involves assessing whether AWJ-SG can satisfy the conditions required for end-of-waste or by-product status. This evaluation considers the intended application of the material, compliance with technical standards, and the absence of environmental or health risks. Preliminary technical results (Baera et al., 2026a) indicate that, following appropriate processing and grading, AWJ-SG may meet these conditions, supporting its potential recognition as a secondary resource within circular construction practices.

AWJ-SG Aggregate Compliance

For construction applications, the processed material must demonstrate compliance with the relevant European aggregate standards. In the case of cement-based mortars, this includes EN 13139 - Aggregates for mortars, while potential applications in concrete require evaluation according to EN 12620 - Aggregates for concrete.

The application of these standards, in conjunction with Regulation (EU) No. 305/2011 (CPR) and relevant national legislation, entails:

- initial type testing (ITT) for essential characteristics (grain size, fines content, sand equivalent, absorption, chloride content, sulfate content, total sulfur, hazardous substances, etc.);
- implementation of a Factory Production Control (FPC) system;
- obtaining FPC certification through the AVCP 2+ system;
- issuing the Declaration of Performance (DoP) and affixing the CE marking.

Therefore, artificial/recycled aggregate cannot be lawfully used in construction mixtures without demonstrating, through documented evidence, compliance with the requirements of

the applicable harmonized standards and the consistency of its performance. Ongoing research aims to further assess the conformity of AWJ-SG with these standards and to define the quality control measures required for its use as a secondary aggregate.

Mortar/Composite Compliance

Beyond aggregate-level requirements, the performance of mortars incorporating AWJ-SG must comply with the relevant product standards, depending on the intended application. The incorporation of 30-50% of recycled garnet aggregate AWJ-SG into hydraulic-binder-based mortars results in a new product that is distinct from a regulatory standpoint and must be evaluated and certified separately from the raw material used. Depending on the mortar's intended use, the following harmonized standards apply: EN 998-1 for rendering and plastering mortars, EN 998-2 for masonry mortars, and EN 1504-3 for repair mortars used in concrete structures.

In this context, certification of the final product involves:

- determination of mechanical performance (compressive strength, adhesion, modulus of elasticity, etc.);
- evaluation of physical properties (density, capillary absorption, vapor permeability, shrinkage);
- verification of durability (freeze-thaw cycles, compatibility with the substrate);
- determination of the performance class (e.g., M5, M10, CS II, R3, R4, etc., as applicable);
- implementation of the system for assessing and verifying the constancy of performance appropriate to the product;
- issuing a separate Declaration of Performance for the resulting mortar.

It is essential to emphasize that the aggregate's compliance with EN 12620 or EN 13139 does not automatically imply the resulting mortar's compliance with EN 998 or EN 1504. The performance of the final product must be demonstrated experimentally and certified independently.

Preliminary laboratory results suggest that SG-based mixtures can achieve the required performance levels, although further testing is necessary to confirm compliance under broader application scenarios.

Product Certification and Conformity Assessment

The final stage of the regulatory pathway concerns product certification and conformity assessment in accordance with Regulation (EU) No. 305/2011 (Construction Products Regulation – CPR). This process addresses both the certification of the aggregate component and the verification of the performance of the final mortar-based product. Future research will therefore focus on identifying the appropriate certification procedures and factory production control requirements necessary for the market placement of AWJ-SG-based construction materials.

Overall, the regulatory layer highlights the legal and conformity conditions required to enable the circular valorisation of AWJ-SG, while also defining the main directions for further investigation needed to support its transition from waste management practices toward certified construction products.

III. Commercial Layer: AWJ-SG Waste-to-Product Transition

The commercial dimension of AWJ-SG valorisation addresses the practical conditions required to move from laboratory validation and regulatory compliance toward market implementation. At the current stage of the research project, the commercial layer remains *exploratory*, identifying potential pathways for integrating AWJ-SG into construction material value chains. The results presented here therefore outline preliminary directions for further investigation, reflecting the multidisciplinary approach adopted within the project.

The cost-benefit analysis of AWJ-SG Valorisation in construction materials and products is currently ongoing, based on comparative assessments against conventional aggregates. No definitive conclusions are available at this stage.

Supply-Chain Integration

Initial assessments indicate that the effective valorisation of AWJ-SG requires the integration of abrasive waterjet processing facilities with waste recovery operators and construction material producers. Establishing these logistical links is essential to ensure that the recovered material can be collected, processed, and

supplied in a consistent form suitable for use as a secondary aggregate. Further investigations will focus on identifying the most efficient configurations for such supply-chain integration at regional or industrial scales.

Stakeholder Engagement

Preliminary consultations highlight the importance of involving key stakeholders, including AWJ operators, waste management companies, construction material manufacturers, and regulatory bodies. Stakeholder engagement is particularly relevant for building confidence in the technical performance and environmental safety of SG-based materials. Continued dialogue with these actors will be necessary to support knowledge exchange and to facilitate acceptance of secondary aggregates within the construction sector.

Supply Chain Organisation

The analysis also suggests that the establishment of a structured supply chain is required to ensure the consistent availability and quality of AWJ-SG. This includes defining standardized collection, processing, and quality control procedures for the recovered material. Future work will therefore examine potential operational models capable of maintaining stable supply while meeting the technical and regulatory requirements identified in the previous layers.

Business Model Development

Several potential business models have been identified as promising directions for the valorisation of AWJ-SG. These include collaborative arrangements between AWJ service providers and mortar producers, waste recovery partnerships, or circular economy platforms promoting the reuse of industrial by-products. In addition, social entrepreneurship initiatives may represent a viable pathway, particularly where waste recovery and processing activities can generate local employment and support community-based circular economy practices. Further research will evaluate the economic feasibility and scalability of these models.

Market Adoption of AWJ-SG-Based Construction Materials

The market uptake of SG-based construction materials will ultimately depend on demonstrating technical reliability, regulatory compliance, and economic competitiveness compared with conventional materials. Although preliminary results indicate that SG-based mortars meet the required performance levels, broader market acceptance will require additional validation, pilot-scale production, and stakeholder engagement. Consequently, the commercial layer remains an ongoing research direction, aimed at identifying the conditions under which AWJ-SG can be successfully integrated into construction markets and contribute to circular economy practices in the sector.

CONCLUSIONS

This study investigated the potential valorisation of abrasive waterjet spent garnet (AWJ-SG) as a secondary fine aggregate in cement-based mortars, adopting a multidisciplinary approach that integrates technical validation, regulatory assessment, and commercial considerations. The results confirm that the transition of AWJ-SG from an industrial waste stream to a construction resource is technically feasible and conceptually supported by the existing legal and market frameworks, although further investigations are required to advance toward full industrial implementation.

From a technical perspective, the laboratory investigations demonstrate that processed AWJ-SG exhibits physical and mineralogical characteristics compatible with conventional fine aggregates used in cement-based mortars. Mortar mixtures incorporating SG at partial replacement levels showed acceptable fresh and hardened performance, confirming the compatibility between SG particles and the cementitious matrix. The validation framework based on repeatability, reliability, performance pattern, and robustness further confirmed the consistency of SG-based mortar prototypes at laboratory scale, providing a solid basis for subsequent pilot-scale investigations.

Beyond the material performance assessment, this study contributes to the integration of circular economy principles into construction material design. By proposing the reuse of AWJ abrasive residues as secondary aggregates, the research demonstrates the potential for industrial symbiosis between manufacturing processes and construction material production, contributing to reduced landfill disposal and decreased consumption of natural aggregate resources.

A key contribution of the work lies in the analysis of the regulatory pathway for waste-to-product transition. The study identifies the legal framework governing the classification, recovery, and certification of AWJ-SG-based materials within the European construction sector, highlighting the relevance of waste classification procedures, end-of-waste or by-product assessments, compliance with aggregate and mortar standards, and product certification in accordance with Regulation (EU) No. 305/2011. This regulatory mapping clarifies the conditions under which SG-based materials could be placed on the market as compliant construction products.

In addition, the research explores the commercial dimension of SG valorisation, identifying key elements required for practical market integration. These include supply-chain organisation, stakeholder engagement, the development of viable business models-including potential social entrepreneurship initiatives-and the gradual market adoption of SG-based construction materials. Although this component of the study remains at an exploratory stage, it provides an initial framework for understanding the economic and organisational conditions necessary for successful implementation. One limitation of this study is that the economic assessment of AWJ-SG valorisation has not yet been completed. Comparative analyses with conventional aggregates are currently underway, and definitive conclusions regarding the cost–benefit performance are therefore beyond the scope of the present work.

Overall, the research proposes a three-layer technology-transfer framework-technical, regulatory, and commercial-designed to support the practical implementation of AWJ-SG valorisation within a circular economy context. By combining laboratory validation with regulatory analysis and preliminary commercial considerations, the study contributes to bridging the gap between experimental material research and real-world industrial application.

Future work will focus on pilot-scale assessments and industrial implementation, further evaluation of regulatory compliance pathways, and the development of operational supply chains capable of supporting the market introduction of SG-based construction materials. Through these continued investigations, AWJ spent garnet may evolve from an industrial waste stream into a valuable resource for sustainable construction practices.

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