



UDC 691.5:666.972.16  
DOI: 10.56318/as/4.2025.21

ISSN: 2411-801X  
e-ISSN: 2786-7374

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## Dry building mixes with secondary raw materials for building renovation: Comparative analysis of properties and efficiency

**Abstract.** The aim of the study was to provide a theoretical assessment of the use of recycled construction and industrial waste in dry renovation mixes. The methodology covered a comprehensive approach to waste utilisation in the context of sustainable development and identifying prospects for Ukraine. It was found that partial replacement of cement with granulated blast-furnace slag (25-50%) reduces the carbon footprint by 30-40% without loss of strength and durability, while the addition of recycled aggregates (20-30% of natural sand) ensures a strength  $\geq 10$  MPa, provided that grading and cleanliness were properly controlled. The combination of glass and slag increases matrix density and reduces water absorption, but requires monitoring of alkali reactivity. Life-cycle analysis has shown a 20-40% reduction in CO<sub>2</sub> emissions, when recycled raw materials are used, while substantial savings of primary resources decreases environmental pressure and waste volumes. The use of methods of mathematical experimental design made it possible to select optimum formulations more rapidly, reducing the number of experiments by a factor of 8-10. Field tests in Portugal, India and the Republic of South Africa confirmed the feasibility of using mixes with secondary materials in plastering and masonry works. In Ukraine, the potential for applying such technologies was considerable in view of post-war reconstruction needs and the availability of large volumes of construction and demolition waste. The most promising solutions for renovation mixes were granulated blast-furnace slag; classified fine fractions (which, after cleaning, can replace 20-30% of sand without loss of properties); combinations of granulated blast-furnace slag and glass powder; and formulations optimised using machine learning. In Ukraine, the main barriers were the insufficient level of quality control and a weak laboratory base; however, regional mix-manufacturing plants were able to ensure effective use of construction waste in reconstruction. The practical significance lies in the possibility of using the results by construction companies and material producers for environmentally friendly mixes and for restoration standards

**Keywords:** waste utilisation; alternative binders; mortar durability; laboratory tests; field tests; resistance to aggressive environments; resource efficiency

### Suggested Citation:

Sobol, Kh., Melnyk, A., & Khita, O. (2025). Dry building mixes with secondary raw materials for building renovation: Comparative analysis of properties and efficiency. *Architectural Studies*, 11(4), 21-32. doi: 10.56318/as/4.2025.21.

Journal homepage: <https://arch-studies.com.ua/en>

*Architectural Studies*, 11(4), 21-32

Received: 09.07.2025 Revised: 31.10.2025 Accepted: 19.12.2025 Published: 29.12.2025

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## INTRODUCTION

In the context of growing scarcity of natural resources and the need to reduce the carbon footprint, the construction industry was increasingly oriented towards the principles of sustainable development. One of the key directions was the use of secondary raw materials in the production of dry building mixes, widely applied in plastering, masonry and repair-renovation works, which was particularly relevant for countries with large volumes of construction waste and a need for large-scale infrastructure restoration. In Ukraine this problem became even more critical due to war-related destruction, which had generated significant flows of construction debris potentially suitable for reuse in production processes.

In the international discourse there have been a number of attempts to systematically assess the potential of such materials. D. Duan *et al.* (2022) showed that the use of fly ash, carbide slag and gypsum from flue-gas desulphurisation units made it possible to produce dry mixes with acceptable mechanical characteristics, while simultaneously reducing cement consumption. This indicated the considerable potential of industrial waste as active mineral additives. A. Pietrzak & M. Ulewicz (2025) demonstrated that using ash from municipal solid-waste incineration together with cement-kiln dust produced environmentally friendly mortars that retained strength at the level of traditional ones, but required careful control of harmful impurities. This approach confirmed the feasibility of re-using industrial waste streams, while at the same time outlining barriers associated with the quality and standardisation of secondary raw materials.

A significant line of technological development remained the activation of slags as alternative binders. In a pilot study, J. Sengupta *et al.* (2024) proved that the use of granulated blast-furnace slag in combination with soda and hydrated lime provided strengths of around 40 MPa, while reducing the cost of the mixes. This meant that even relatively simple and accessible activators can ensure efficiency comparable with that of expensive alkali-activation systems, which opened up prospects for practical implementation in resource-constrained countries. Equally promising was the use of recycled aggregates and powders. Z. Ma *et al.* (2023) analysed the possibility of using waste from high-quality mortars in new cement systems and showed that this approach significantly affected the material's microstructure and chloride-transport processes, which determined the durability of structures. The repeated use of finely dispersed demolition products can not only reduce the demand for natural resources, but also increase resistance to reinforcement corrosion. This broadened understanding of the role of microstructural changes in shaping performance characteristics and outlined prospects for further work in the field of renovation materials.

The greening of plaster mortars through the use of alternative raw materials has been the subject of research by N.A. Valoni *et al.* (2025). The authors found that microstructural parameters directly influenced the mechanical

properties and durability of the material, and that appropriate selection of components makes it possible to combine high strength with environmental benefits. This formed the concept of balancing microstructural and performance characteristics as a key guideline for creating eco-friendly mixes for renovation. V. Grigorjev *et al.* (2025) focused on the use of recycled fine fractions as a replacement for natural aggregates in cement-lime mortars. Researchers found that the resulting compositions maintain an adequate level of strength and adhesion, sufficient for use in masonry and repair works. This confirmed the possibility of integrating secondary materials into traditional binder systems, which was a step towards implementing circular-economy principles in construction practice.

In Ukrainian academic discourse there was also a growing interest in the use of secondary resources in construction materials. A. Melnyk *et al.* (2024) presented dry mixes for flooring elements, which partly incorporate secondary components, confirming the possibility of their practical use in innovative structural solutions. In the study by M. Oleksyn & Z. Obynochna (2023), practices of using secondary raw materials in architecture and construction were summarised, with an emphasis on the combination of environmental and economic advantages of this approach. Ukrainian publications highlighted the lack of a sufficient body of field tests and standardised quality-control procedures, which complicated the scaling up of such solutions. Despite the existence of research results, the practical integration of secondary materials into dry building mixes for renovation tasks remains limited. Existing studies showed progress in creating mixes with waste, but at the same time outline several unresolved issues: durability under real service conditions, variability of raw-material properties and the risk of undesirable chemical reactions (in particular, alkali-aggregate reaction). In Ukraine these challenges were exacerbated by the scale of destruction and the absence of an effective waste-sorting system. Therefore, the aim of this study was to theoretically determine the possibilities and limitations of using secondary raw materials in dry mortars for restoration works.

## MATERIALS AND METHODS

The study employed a comprehensive approach, which involved using methods of analysis and synthesis to assess the possibilities of integrating secondary raw materials into dry building mixes, determined their properties and identify promising directions for implementation in the context of Ukraine's post-war reconstruction. To characterise regulatory requirements, a comparative-analysis method was used, enabling the systematisation of EU and European Economic Area standards – European Standard EN 197-1:2011 (2011), European Standard EN 998-1:2016 (2016), and Ukrainian national standards – DSTU B V.2.7-126:2011 (2011), DSTU EN 998-2:2023 (2024). These documents were selected because they regulate the key characteristics of cement and mortars for masonry and plastering



that were directly related to the use of secondary materials in dry mixes. Comparing the requirements made it possible to identify differences between European and Ukrainian standards and to outline directions for further adaptation of regulations to the conditions of post-war reconstruction.

To systematise international experience, the comparative-analysis method and the case-study method were applied to examine practical implementation models in various countries (India, Portugal, Saudi Arabia, Australia, Brazil, the Republic of South Africa, Pakistan, Switzerland, France, and Ukraine). Key aspects of the use of waste in renovation mixes were identified, gaps (technical, environmental or regulatory) were revealed and real examples of application were presented. The choice of countries was justified by the fact that it represented different types of approaches:

- 1) states with large volumes of waste and a need for its utilisation (India, Pakistan, Brazil, Republic of South Africa);
- 2) countries with developed EU-level standards (Portugal, France, Switzerland);
- 3) innovation-oriented countries with an emphasis on digitalisation (Saudi Arabia and Australia);
- 4) Ukraine as a practical centre for applying international experience in post-war reconstruction.

This was done in order to compare international experience in the use of secondary materials in renovation mixes, to identify effective technologies and solutions that can be scaled up in Ukraine, to identify weaknesses and to assess practicality of implementation (strength, durability, functional properties, limitations/risks, practical cases of use in the countries concerned that indicated potential scalability and compliance with regulatory requirements), taking local conditions (post-war rebuilding) into account. International experience and characteristics of secondary raw materials were analysed specifically from the standpoint of their suitability for use in dry building mixes. Methods of analysis and synthesis of academic sources were used to systematise approaches to the utilisation of construction and industrial waste in building mixes: the use of industrial by-products (slags, power-station fly ash, metallurgical waste) as supplementary cementitious materials; the integration of waste into the materials-science cycle within the concept of the circular economy; the combination of laboratory and field tests to verify the suitability of mixes; the combination of different waste fractions to achieve synergistic effects; and the application of digital technologies and machine learning to optimise formulations according to criteria of technical performance (strength, durability, water absorption), environmental impact (reduction of carbon footprint, reduction of waste), economic feasibility (replacement of expensive primary materials) and regulatory potential (compliance with standards and the possibility of further standardisation). This made it possible to identify key opportunities for reducing dependence on traditional non-renewable materials and to form guidelines for the development of innovative technologies in the context of post-war reconstruction.

To characterise the various types of secondary materials used in dry building mixes, a comparative-analysis and systematisation method was applied on the basis of data from scientific publications: reclaimed cement powder and reclaimed fine aggregate from construction waste; different fractions of recycled construction debris; recycled glass in combination with granulated blast-furnace slag; glass, granite and marble powders; supplementary cementitious materials (slags, ash) in dry mixes; blast-furnace slag and crushed concrete scrap; waste for lightweight and insulating mortars (expanded polystyrene, perlite); construction waste combined with digital optimisation of composition (machine learning); and waste powders (glass, ceramics, stone) as cement replacements. The criteria used were: ranges of cement and sand replacement; strength; conditions of testing (laboratory research, life-cycle assessment, modelling); limitations and risks; and the readiness level of each approach (assessed using the Technology Readiness Level scale, ISO 16290:2013 (2013); in most cases it corresponds to a “medium” level – confirmed by laboratory and modelling tests but without long-term standardisation). The materials and criteria were selected to ensure a balance between environmental effect (waste utilisation, reduction of carbon footprint) and technical feasibility (strength, durability, standardisation). The aim of this stage was to create a consolidated knowledge base allowing different types of secondary raw materials to be compared according to key indicators. This made it possible to identify the strengths and weaknesses of each material, assess their suitability for different types of building mixes and determine, where further standardisation or optimisation was required. To classify promising directions (slags, glass powders, fine classified fractions) and identify key challenges (variability of raw materials, increased water demand, risks of chemical instability, sorting costs), an analytical-synthetic method was used. In addition, a forecasting approach was applied to determine optimal material platforms (granulated blast-furnace slag as a supplementary cementitious material; classified and washed fine fractions of construction and demolition waste as sand replacements; limited addition of glass powder as a reactive component) for renovation mixes and to outline guidelines for further research. The task of this stage was to delineate the boundaries of existing studies and to identify promising directions for the use of secondary raw materials in dry building mixes, as well as to identify key challenges and gaps. This made it possible to formulate benchmarks for subsequent work.

## RESULTS AND DISCUSSION

### Circular economy, waste utilisation and standardisation of renovation mixes

The utilisation of construction and industrial waste was not only a technological, but also a conceptual task in the field of sustainable development. Turning waste into resources was seen as a key direction for reducing the carbon footprint of the construction sector. Secondary raw materials can perform a dual function: on the one hand, reducing





dependence on traditional non-renewable materials (cement, natural sand, aggregates), and on the other, minimising the negative environmental impacts of landfilling or incineration (Fernando *et al.*, 2025). A more detailed examination of approaches to the use of industrial by-products (slag, power-station fly ash, metallurgical waste) in the production of building mixes shows that these materials can not only replace part of the cement or aggregates, but also act as functional additives, improving specific properties of materials such as water resistance and durability in aggressive environments. Conceptually, waste utilisation was viewed as integrating waste into the materials-science cycle rather than simply “disposing” of it (Yeo *et al.*, 2023).

Applying waste through the prism of the circular economy implied a shift from a linear model (“production – use – disposal”) to an approach, in which materials were repeatedly reintroduced into the production cycle. In the case of building mixes, this meant the possibility of repeatedly converting structural waste into secondary aggregates and binders. The circular economy in construction had not only an environmental dimension, but also a socio-economic one. It contributed to reducing the need for extraction of primary resources, creating new value-added chains and lowering the burden on waste-management infrastructure. In addition, such an approach stimulated the development of new regulations and standards capable of integrating waste into formalised requirements for the quality of dry building mixes (Bansal *et al.*, 2024). At the theoretical level, the use of secondary raw materials in dry building mixes was considered part of a broader strategy for transforming the construction industry towards a circular-economy model, in which waste ceased to be an end product and became a resource for new production.

The use of secondary aggregates obtained from construction debris under real site conditions brought the focus onto the transition from laboratory experiments to practical field trials. This made it possible to assess not only the physical and mechanical properties of the resulting mortars, but also the effectiveness of technological processes on site. One specific feature of this approach was taking into account the heterogeneity of secondary raw materials and adapting technological parameters to real conditions. This demonstrated the scalability of solutions and underlined the need for flexible technological approaches (Chen *et al.*, 2024). Combining technical and environmental assessment of mortars made from recycled construction debris made it possible to achieve acceptable mechanical characteristics, while simultaneously reducing the carbon footprint. Such an approach emphasised the importance of an integrated perspective, in which technical feasibility was assessed alongside environmental performance, reflecting the growing trend to evaluate materials in the context of sustainable development (Ohemeng *et al.*, 2024).

The impact of using blast-furnace slag and crushed concrete rubble in mortars showed that partial cement replacement with slag can significantly reduce primary-resource consumption, while ensuring an acceptable level

of strength. The use of concrete rubble as a fine aggregate improved waste utilisation without a significant reduction in performance characteristics (Farooq *et al.*, 2023). The combined use of waste glass and blast-furnace slag in dry building mixes had shown that such a combination can be effectively employed in the production of environmentally friendly building materials. This made it possible to reduce the environmental impact of these materials and to use large volumes of secondary raw materials without critical deterioration in properties, and demonstrated the potential of combined use of different waste streams to create multifunctional solutions (Baah *et al.*, 2025).

The standardisation of dry mixes containing supplementary cementitious materials obtained from industrial waste was a crucial aspect for the development of this technology. This raised questions not only of technical efficiency, but also of the need to regulate the use of such materials. The establishment of standards may become a key factor for large-scale implementation, since without harmonised regulations their practical use will remain limited (Antunes *et al.*, 2024). Analysis of the properties of blended mortars made from waste from different streams showed that a multicomponent approach made it possible to achieve synergistic effects, where the drawbacks of one type of waste were offset by the advantages of another. This approach was an example of seeking an optimal balance between technical and environmental indicators and can serve as a basis for creating new mix designs that reflected the complex structure of waste under real-world conditions, as noted by K. Zhang *et al.* (2023).

An innovative direction associated with the use of machine learning for optimising mortar compositions showed that adaptive algorithms can significantly accelerate the selection of effective formulations, reducing the need for large numbers of experimental tests. This opened up a new perspective for the integration of digital technologies into materials science and paved the way for the “personalised” selection of formulations, depending on the available raw materials (Abbas, 2025). Predictive modelling of the mechanical properties of cement replacements derived from waste showed that mathematical models were able to forecast material behaviour with a high degree of accuracy, making them a valuable tool for pre-selecting technological solutions. This approach was a logical extension of the concept of the digitalisation of the construction sector, where empirical data were combined with intelligent algorithms (Ranasinghe *et al.*, 2024). Multidimensional analysis of the properties of mortars containing recycled waste covered not only mechanical, but also thermal and chemical characteristics, allowing a comprehensive assessment of materials. The integration of waste was not limited to strength indicators; rather, it shaped a broader range of performance parameters that determined the suitability of mixes for renovation works (Wu *et al.*, 2025). To summarise approaches to the utilisation of construction and industrial waste, Table 1 presented types of raw materials, replacement ranges, properties, limitations and readiness level for use in renovation mixes.

**Table 1.** Characteristics of secondary materials for dry building mixes

Type of waste	Replacement range	Strength	Conditions	Limitations/risks	Readiness level
Reclaimed cement powder and reclaimed fine aggregate from construction waste	20% of cement, 100% of sand	With 20% replacement of cement by reclaimed powder, strength increased by 8%. With 100% sand replacement, water absorption and density decreased	Laboratory tests	Strict quality control of secondary fractions is required	Medium
Various fractions of recycled construction debris	Replacement of sand with recycled aggregate at 25%, 50%, 75% and 100%	As the proportion of recycled aggregate increased, there was a gradual decrease in strength and an increase in water absorption	Laboratory studies + life-cycle assessment	Additional cleaning and sorting of secondary materials are required	Medium
Recycled glass in combination with granulated blast-furnace slag	Approx. 91% glass and 26% slag (optimum conditions)	Achieved strength of about 36.5 MPa, reduced water absorption, denser structure	Laboratory tests	Risk of alkali-aggregate reaction of glass	Medium
Glass, granite and marble powders	5-15% of cement, 10-30% of sand	At 5-10% glass, strength increased (by 11% at 28 days); granite above 10% reduced strength, marble above 10% increased water absorption	Laboratory tests	Critical importance of fineness of grinding	Medium
Supplementary cementitious materials (slag, ash) in dry mixes	15-50% of cement replaced by waste	Slight reduction in early strength; in the long term, increased density and reduced permeability	Laboratory studies + analysis of regulatory requirements	Need for standardisation and regulation	Medium
Blast-furnace slag and crushed concrete rubble	Several levels of cement and sand replacement	Reduced consumption of primary resources, acceptable strength	Laboratory tests with environmental assessment	Limited data on durability	Medium
Waste for lightweight and insulating mortars (expanded polystyrene, perlite)	Depending on waste type	Mechanical, thermal and chemical properties analysed comprehensively; risks of reduced strength at high contents of lightweight fractions identified	Laboratory tests	Possible issues with durability and compatibility	Medium
Construction waste combined with digital optimisation of composition (machine learning)	Adaptive replacement ranges	Normative strength achieved; the speed of formulation selection increased by about a factor of 10 compared with traditional experimental methods (series of mixes and trial-and-error testing)	Laboratory tests + modelling	Effectiveness depends on the quality of input data	Medium
Waste powders (glass, ceramics, stone) as cement replacements, application of machine learning	5-50% of cement	An optimum of 10-15% gives the best results; models accurately predict properties	Laboratory tests + modelling	Stable data sets required	Medium

**Note:** “normative strength achieved” means that in tests with digital optimisation of compositions (machine learning), the values obtained fell within the range defined by European Standard EN 197-1:2011 (2011) for the specific type of mortar, typically 7-10 MPa and above for masonry and repair mortars

**Source:** based on O. Farooq *et al.* (2023), J.S. Yeo *et al.* (2023), S. Bansal *et al.* (2024), A. Antunes *et al.* (2024), E.A. Ohemeng *et al.* (2024), R.C. Malladi *et al.* (2025), P.M. Borges *et al.* (2025), T.T. Baah *et al.* (2025), M.M. Abbas (2025)

Most secondary materials provided acceptable technical characteristics and a medium level of technological readiness; however, their effectiveness depended on quality control, cleaning and standardisation. The most promising systems were those with blast-furnace slag, glass and digitally optimised compositions, while the main constraints remained raw-material variability and long-term durability. At the same time, the key challenges continued to be the variability of waste properties, limited durability data and the lack of standardised procedures for large-scale implementation. Assessing the feasibility of using secondary materials in dry building mixes required consideration of current standards that defined requirements for composition, properties and quality control. At

international level, the basic documents were European Standard EN 197-1:2011 (2011), which defined the composition and conformity criteria for common cements, including requirements for clinker and mineral additions, and European Standard EN 998-1:2016 (2016), which regulated the properties of plastering and renovation mortars, including requirements for strength, adhesion, water absorption and durability. The Ukrainian regulatory framework was harmonised with the European one, but also had its own standards: DSTU B V.2.7-126:2011 (2011) regulated the properties of mortars used in construction, including strength, workability and durability; DSTU EN 998-2:2023 (2024) provided the basis for regulating the quality of masonry mixes in Ukraine in line with European requirements.





European standards provided the methodological foundation, while Ukrainian documents required further adaptation and harmonisation to take into account the specifics of local waste streams and post-war reconstruction tasks.

The results of the study showed that waste utilisation was understood not as disposal but as integration into the materials-science cycle. This approach goes beyond the traditional concept of “getting rid of rubbish” and forms a new logic of the circular economy. This correlated with the work of N. Ranasinghe *et al.* (2024), who emphasised the critical importance of data traceability and transparent control mechanisms, without which genuine circularity cannot be achieved. The authors demonstrated that simply incorporating secondary raw materials does not guarantee sustainable development if compliance with standards and quality control at all stages of the life cycle is not ensured. The concept of “waste as a resource” can become the methodological basis for transforming the construction sector. The combination of materials-science integration, traceability and digital control tools forms the key to an effective transition of construction to a circular-economy model.

In the study by J. Wu *et al.* (2025) it was underlined that existing approaches to the use of secondary materials in construction cannot be limited exclusively to mechanical parameters, since sustainable development requires simultaneous consideration of environmental, energy and durability criteria. The authors found that integrating multidimensional indicators – from strength and adhesion to carbon footprint and resource efficiency – was becoming a global standard in scientific research and practical development. This corresponded to the results of the present study, according to which field tests on construction sites demonstrated the feasibility of an integrated approach combining technical and environmental assessment of mortars. This made it possible not only to establish compliance of materials with regulatory requirements for strength or water absorption, but also to evaluate their actual behaviour in field conditions, taking long-term environmental impacts into account, and indicated the need for a multidimensional assessment of material performance, in which environmental sustainability and resource efficiency were as important as technical characteristics.

The results of the study established that the use of waste through the prism of the circular economy implies a shift from the linear model “production – use – disposal” to repeated reintroduction of materials into the production cycle, which significantly reduced the burden on natural resources and waste-management infrastructure. This aligned with H. Shajidha & M. Mortula (2025), who stressed that the effectiveness of circular solutions is determined not only by the level of innovative technologies, but also by the quality of systemic management. The authors emphasised that public policy, regulatory mechanisms and economic incentives were critical factors in scaling up such practices in different countries. This meant that technological solutions in the field of waste reuse must be accompanied by institutional support that ensured the integration of

circular models into construction standards and infrastructure programmes. Accordingly, the circular economy in construction was emerging as a multilevel system that combined materials-science innovation, management strategies and political instruments of sustainable development.

R.M. Cigala *et al.* (2025) showed that geopolymers produced from industrial waste, particularly from secondary sources of silicates and aluminates, can provide increased resistance to aggressive environments, while forming a dense matrix with improved performance properties. Such materials do not merely act as replacements; they serve as active modifiers of the structure of building mortars, creating a new functional level of application. This resonated with the present study, in which it was found that the use of blast-furnace slag and crushed concrete allowed a significant reduction in primary-resource consumption, while maintaining acceptable physical and mechanical properties. Both studies confirmed that industrial waste can play a role not only in reducing environmental impact, but also in creating materials with additional functional characteristics.

The results of the study showed that key barriers to the widespread introduction of secondary materials into dry building mixes remain the absence of specialised standards and regulations capable of formalising requirements for the quality and durability of such solutions. Even, where experimental formulations were technically successful, their scaling was blocked by legal and regulatory uncertainty, which created risks for both manufacturers and consumers. This was consistent with G.C.R. Hasibuan *et al.* (2025), who emphasised that the lack of regulatory infrastructure was one of the main obstacles to the practical integration of circular-economy principles into the construction sector. Scientists noted that the absence of unified protocols and harmonised requirements led to fragmented solutions and limits the possibility of their international recognition. This meant that even the most convincing technological advances will not have the potential for wide application without systematic adaptation of standards, which must encompass both local conditions and global regulatory approaches. Thus, the recycling of construction and industrial waste emerged as a key mechanism for developing the circular economy, simultaneously reducing environmental risks and opening the way to creating materials with enhanced functional properties. However, the absence of harmonised standards and adequate control mechanisms significantly limited the prospects for large-scale application, even of technologically effective solutions.

#### **Assessment of suitability and global experience of using secondary raw materials, with adaptation to the conditions of Ukraine**

The key criterion for the suitability of secondary raw materials in dry renovation mixes was durability. The use of recycled fillers and supplementary cementitious materials (slag, fly ash, microsilica) can alter the degradation mechanisms of the matrix, accelerate carbonation and cause sulphate attack in the presence of gypsum-bearing impurities;



in systems with crushed glass, the risk of alkali-aggregate reaction remains. For this reason, tests were required for resistance to carbonation, sulphates and frost, as well as checks of adhesion and shrinkage with the use of inhibitors and modifiers. Field data have confirmed that replacing 20-30% of natural sand with recycled aggregates ensured a strength of 7-10 MPa, while laboratory tests have demonstrated higher values for systems with granulated blast-furnace slag and glass (Chen *et al.*, 2024; Abbas, 2025).

Replacing 25-50% of clinker with slag reduced the carbon footprint by 30-40% without loss of durability, and the thermal conductivity of materials can fall to 0.35-0.4 W/m-K, while maintaining strength above 15 MPa. To reduce variability, standardised procedures were needed for sorting, cleaning and classification of fractions, control of sulphate, organic and salt content, as well as incoming inspection protocols with “batch passports”. The use

of machine learning speeded up formulation selection several-fold and increases reproducibility, but required high-quality stable data and integration with field monitoring. Overall, the use of 20-30% recycled aggregates and 25-50% granulated blast-furnace slag was recognised as appropriate, providing strengths of 10-20 MPa and a 20-40% reduction in carbon dioxide emissions (Ohemeng *et al.*, 2024). Global experience showed significant differences in the use of construction and industrial waste for producing dry mixes. Different countries have developed their own approaches to replacing cement and natural aggregates, depending on the local raw-materials base, climatic conditions and regulatory infrastructure. The synthesis in Table 2 made it possible to trace strengths, existing gaps and practical examples of technological applications, forming a basis for adapting effective practices to the conditions of Ukraine.

**Table 2.** Characteristics of international studies on the use of waste in renovation mixes

Country	Key aspects	Gap	Real-world examples
India	Recycling of construction waste: 20% replacement of cement by reclaimed powder (+8.07% compressive strength), 100% sand replacement (-11.48% water absorption, -5.21% porosity); acid separation method for a closed-loop economy	Resistance to freeze-thaw cycles in a continental climate; combination with supplementary binders for hybrid repair mortars	Laboratory tests; recycled construction waste in mortars for façade repair (global life-cycle assessment models)
Portugal	Recycled aggregates (concrete, brick, ceramics): replacement of natural sand up to 100% with adjustment of water-cement ratio (0.15% per % of recycled aggregate), laboratory and field adhesion/capillarity tests	Long-term adhesion in historic masonry (over 5 years); impact on vapour permeability in energy-efficient renovation	Field trials: mortar with recycled aggregates for plastering/masonry in Portugal; use of recycled aggregates in masonry mortars for renovation in Europe
Saudi Arabia	Waste (ceramics, glass, granite, marble, brick) as cement replacements: 5-50% replacement (optimum 10-15%), strength prediction using machine learning (neural networks)	Stability of machine-learning models for local wastes; combination with additives against alkali-aggregate reaction for renovation adhesives	Laboratory modelling; prediction of properties of mortars with waste in construction projects (pilot tests in Saudi Arabia)
Brazil	Fine recycled aggregates from construction waste: 25-100% sand replacement, life-cycle assessment (84-337 kg CO <sub>2</sub> /m <sup>3</sup> ), carbonation tests (3% CO <sub>2</sub> )	Water demand under high humidity; additives against sulphate attack to ensure durability in renovation	Laboratory tests with life-cycle assessment; mortars with recycled aggregates for building repair
South Africa	Blast-furnace slag + concrete rubble: 60% rubble + 10% slag, -12.8-32.5% strength, -4.5% water absorption, life-cycle assessment	Durability of concrete rubble under freeze-thaw cycles	Laboratory environmental tests; mortars with concrete rubble for robust renovation
Pakistan	Blended mortars with waste (glass, granite, marble): 5-15% of cement, 10-30% of sand; strength increase, structural analysis	Rheology under high humidity; multicomponent mixes for levelling layers in renovation	Laboratory structural tests; blended mortars for renovation layers
Australia	Recycled glass + fly ash as a suppressant of alkali-aggregate reaction: durability, improved strength	Behaviour in combinations with aggregates; field tests for plasters in renovation	Laboratory durability tests; glass-containing mortars for durable renovation
Ukraine/ Switzerland/ France	Recycled concrete for post-war reconstruction: -10% strength, risks of sulphates/chlorides, 20-30 million m <sup>3</sup> of concrete debris	Standards for fine aggregates; carbonation/heat treatment for stability in the Ukrainian climate	Processing of 50 thousand tonnes of rubble for residential projects; recycling brick/concrete for restoration of “war waste”
Ukraine	Recycling of construction waste: 6% utilisation, crushing/briquetting technologies, secondary materials (rubber, paper, wood, 15,500 J/kg for briquettes). Secondary wastes in dry mixes: diatomite, limestone, quartz sand; + density, -shrinkage, strength class M100+ without additional binders	Recycling centres; integration of secondary materials into dry renovation mixes by 2030, economic model. Resistance to freeze-thaw cycles; optimisation for repair mixes of class M100+ without binders	Rubber crumbs for asphalt; eco-wool from paper for low-rise housing; wood briquettes; concrete rubble. Quarry waste in dry mixes for low-cost renovation

**Note:** M100 is a concrete grade that defines compressive strength. This means that the mix can reach a strength of 100 kg/cm<sup>2</sup> (or 10 MPa) after 28 days of curing. In the case of M100+, this refers to a mix that may have a strength higher than 100 (e.g., 120, 150 kg/cm<sup>2</sup> or more), but without the use of binders

**Source:** based on V. Troian *et al.* (2022), O. Farooq *et al.* (2023), K. Zhang *et al.* (2023), S. Bansal *et al.* (2024), A. Antunes *et al.* (2024), L. Chen *et al.* (2024), A. Bondar *et al.* (2024), W.C.V. Fernando *et al.* (2025), P.M. Borges *et al.* (2025)





The scale and outcomes of using construction waste in dry mixes depended on local conditions and the regulatory framework. The most successful examples were associated with combining laboratory research and field trials, while the key gaps remained long-term durability and the absence of unified standards. For Ukraine, it was appropriate to adapt global experience to post-war reconstruction and to develop regional recycling centres. Despite substantial progress in studying the use of waste in dry building mixes, a number of areas remained under-researched. Although there were individual examples of creating dry-mix systems with secondary raw materials (Yeo *et al.*, 2023; Bansal *et al.*, 2024), there were no comprehensive comparative studies specifically on renovation plastering, masonry and self-levelling mixes. Most works were limited to mechanical properties and water absorption (Antunes *et al.*, 2024; Cigala *et al.*, 2025). There was a lack of comprehensive tests on vapour permeability, salt migration and efflorescence formation on real cultural-heritage objects.

Studies on upcycling binders and modelling compositions using machine learning provided predictive assessments, but there were no field investigations longer than 5-10 years, particularly with regard to freeze-thaw and wetting-drying cycles (Abbas, 2025; Fernando *et al.*, 2025). Despite individual proposals for standardising dry-mix compositions (Bansal *et al.*, 2024) and Ukrainian reviews (Hudym *et al.*, 2022; Bondar *et al.*, 2024), there were no clear methods for controlling contamination of waste and no specialised regulations specifically for renovation mixes. Some studies covered life-cycle assessment and eco-technical aspects, but there were no regionally specific life-cycle assessments for Ukraine that would take into account logistics and the stability of secondary raw-material quality (Ohemeng *et al.*, 2024; Borges *et al.*, 2025). Fire-performance characteristics and scenarios for repeated recycling were also insufficiently studied, although some publications analyse thermal and chemical properties of mixes; systematic research in this area was lacking (Ranasinghe *et al.*, 2024). For instance, N. Kostyra & O. Bashynskyi (2025) investigated the fire resistance of steel floor beams during a building's renovation, underlining the need to address fire performance in reconstruction projects.

Nevertheless, even in the absence of standardisation and long-term trials, secondary materials showed substantial potential. Slags and other supplementary cementitious materials reduced heat release and formed a denser matrix; fine waste fractions effectively replaced natural sand; and combinations of glass and slag reduced water absorption and improved structure. At the same time, challenges remained – variability of raw materials, increased water demand and risks of chemical instability, all of which required control and formulation adaptation. The use of secondary resources helped to reduce the carbon footprint and extraction of primary materials, but high costs of sorting and cleaning slow large-scale implementation, underlining the importance of developing local recycling chains. Among different types of waste, granulated blast-furnace

slag was the most promising for renovation dry mixes. Its effectiveness had been confirmed by field studies and multidimensional assessments: it reduced the carbon footprint by 30-40%, forms a denser matrix and increases durability. Another robust solution was classified and washed fine fractions (0-2/4 mm) of construction and demolition waste, which can replace up to 20-30% of natural sand in plastering and masonry mixes, especially in levelling layers.

Systems based on combinations of granulated blast-furnace slag and glass powder had medium-term prospects: laboratory data showed synergy in reactivity and particle packing, significant strength and low water absorption (Botirov & Botirova, 2024). However, control of the alkali reactivity of glass and the development of unified methods for dry mixes were required. A similar situation existed for multi-stream composites (concrete + ash): it ensured formulation flexibility and the possibility of machine-learning optimisation for local raw materials, but required a well-developed system of incoming quality control. Prospective, subject to risk management, were mixed construction and demolition wastes containing gypsum, wood or organic impurities. It can be used only after aggressive sorting and washing, otherwise there was a high risk of shrinkage, salt-related and sulphate-induced defects. Practical guidelines for designing renovation mixes involved identifying an optimal material platform based on the use of granulated blast-furnace slag in the range of 15-50% of binder mass in combination with classified sand from construction and demolition waste (20-30% of aggregate), with the possible introduction of up to 10% glass powder as a reactive component. Control of rheological properties was achieved through the use of superplasticisers, adjustment of fineness modulus and pre-saturation of recycled sand fractions. Ensuring durability require tests for sulphate and carbonation resistance, adhesion, shrinkage and frost resistance. Quality control presupposes checking impurity content (sulphates, organics, salts), incoming batch-control protocols and the introduction of a “batch passport” system with fixed characteristics. Digitalisation of the process included the creation of databases of local wastes and the use of machine-learning cycles (from design to retraining based on feedback from construction sites). The most convincing and practically substantiated option for renovation mixes was the combination of granulated blast-furnace slag as a supplementary cementitious material with classified fine fractions of construction and demolition waste, whereas systems based on combinations of slag and glass or multi-stream composites required further standardisation and field verification.

In Ukraine, the raw-material base was favourable, but the wastes were characterised by variability of composition (concrete, brick, mixed impurities), which required efficient systems for sorting and cleaning. The regulatory framework does not reflect the specifics of dry mixes with secondary components, creating barriers to certification and wide implementation of the technologies; therefore, adaptation of international standards and the development



of Ukrainian documents that take local waste streams into account are necessary. In logistical and economic terms, a problem was the concentration of large volumes of construction debris in regions of active hostilities, which complicated transport and increased processing costs; at the same time, using such waste as a replacement for natural sand or as partial cement substitution can significantly reduce reconstruction costs. Promising directions included the use of classified and washed sand from construction and demolition waste in plastering and masonry mixes; the use of granulated blast-furnace slag and power-station ash as supplementary cementitious materials to reduce carbon dioxide emissions and lower costs; and the creation of regional centres for sorting and producing dry mixes, integrated into large-scale reconstruction projects. The main risks remained the absence of systematic quality control of secondary raw materials, the lack of laboratory infrastructure for testing and limited possibilities for long-term monitoring of service durability.

The results of the study showed that the effect of blast-furnace slag in combination with recycled aggregates manifested itself in maintaining normative strength even, when 20-30% of natural sand and 25-50% of clinker was replaced. Such a formulation also reduced the carbon footprint by 20-40%, increasing the environmental efficiency of the materials. This correlated with I. Beigh & M.Z. ul Haq (2024), who concluded that partial cement replacement with slag and the use of recycled aggregate stabilise composite structure and made it possible to achieve acceptable strength characteristics in geopolymer systems. Similar conclusions were reported by P. Zhang *et al.* (2023), who emphasised that using recycled aggregate together with slag-based binders reduced permeability, densified the microstructure and enhanced durability, which was consistent with this study. Industrial waste can act not only as a substitute for traditional materials, but also as an active modifier of microstructure. Integrating recycled aggregate and blast-furnace slag was an optimal strategy for creating renovation mixes that combined technical reliability with a low environmental burden.

A.T. Balasbaneh *et al.* (2025) stressed that construction-waste management required a systemic approach based on life-cycle analysis. The authors showed that applying the Life Cycle Sustainability Assessment framework allowed solutions to be evaluated not only in terms of mechanical or economic indicators, but in a broader dimension, taking into account carbon footprint, energy consumption and resource efficiency. The absence of policy incentives and adequate regulatory support hampers scaling up even the most technically sound practices. This corresponded to the results of this study, which showed that combining technical and environmental assessment of materials was necessary, but insufficient without institutional backing. In practical terms, this meant that circular solutions in the field of dry renovation mixes must be implemented in tandem with state programmes and supportive policies. Only the integration of Life Cycle Sustainability Assessment methodology with

management and policy mechanisms can ensure large-scale dissemination and real environmental effectiveness.

The results of the study showed that enhancing durability in dry renovation mixes was directly linked to modifying the composition and introducing functional additives that changed matrix degradation mechanisms. Systems based on granulated blast-furnace slag and crushed glass exhibit higher density, reduced water absorption and improved resistance to sulphate attack, but their effectiveness depended on curing regimes. This was in line with the experimental work of S. Irum *et al.* (2025), which demonstrated that introducing graphite nanoplatelets in combination with optimised heat-curing or ambient-curing regimes significantly increases strength and durability of geopolymer composites made from recycled materials. The authors showed that nanomodifiers not only improve mechanical characteristics, but also form a more stable microstructure with enhanced resistance to long-term freeze-thaw cycles. This meant that combining secondary resources with nano-additives produced a new generation of materials, whose durability was determined not only by composition, but also by controlled structuring mechanisms. Such an approach may become fundamental for renovation mixes adapted to aggressive service conditions.

G. Bonifazi *et al.* (2025) found that key trends in recycling construction and demolition waste include the introduction of high-precision sorting (sensor- and spectroscopy-based technologies), contamination control (gypsum, organics, salts), the formation of “end-of-waste” criteria and harmonised standards, as well as digital traceability of batches. Researchers stressed that variability of secondary raw-material properties and the absence of unified technical specifications remained the main barriers limiting the scaling of even technically mature solutions. This was consistent with the results of this study, which indicated that the durability of dry-mix systems depended on strict control of impurities, standardised sorting procedures and the introduction of “batch passports”. Without harmonised regulations and digital traceability mechanisms, even material platforms, whose effectiveness had been proven in laboratory and field conditions cannot be scaled up at industry level. Thus, integrating recycled construction and industrial waste into dry renovation mixes was a technically and environmentally justified strategy that can simultaneously reduce the carbon footprint and dependence on non-renewable resources. The key conditions for scaling up were standardised sorting and impurity control, incoming inspection protocols and the use of machine learning, and for Ukraine – adaptation of standards and the creation of regional recycling centres.

## CONCLUSIONS

The results of the study have shown that the utilisation of construction and industrial waste in dry mixes made it possible to significantly reduce dependence on primary non-renewable resources and cut the carbon footprint. The transition to a circular economy in construction ensured the reintroduction of waste into the production





cycle. Technical results indicated high effectiveness of secondary materials: 20% replacement of cement with reclaimed powder increases strength by ~8%, whereas 100% replacement of sand with recycled aggregate reduced water absorption and density, although it required careful control. The use of 15-50% slag or fly ash provided a denser matrix and lower permeability in the long term, even if strength decreased at early ages. Combining glass and slag (an optimum proportion of 91% glass and 26% granulated slag yields a strength of ~36.5 MPa) significantly reduced water absorption and formed a denser structure. In addition, the addition of 5-10% glass powder to cement provided ~11% strength growth at 28 days. International experience confirmed the effectiveness of such solutions: in India, 20% replacement of cement by reclaimed powder delivered a strength increase of 8.07%, while 100% replacement of sand led to an 11.48% reduction in water absorption and a 5.21% decrease in porosity. In South Africa, a combination of 60% concrete rubble and 10% slag showed a 12.8-32.5% decrease in strength, but a 4.5% reduction in water absorption.

However, challenges remained: variability in raw-material composition, a lack of long-term durability data (frost resistance, sulphate attack, carbonation), high costs

of sorting and cleaning, and the absence of unified standards. It was necessary to introduce “batch passports”, to control the presence of sulphates, organics and salts, and to regulate the risks of alkali-aggregate reaction of glass. For Ukraine, the most practical and justified approach was to use 15-50% granulated blast-furnace slag in the binder together with 20-30% classified washed sands from construction waste. This approach, combined with the development of regional recycling centres and digital quality control, will make it possible to achieve a balance between strength, durability and environmental efficiency. Further studies should focus on field durability research, the development of standardised quality-control methods, regional life-cycle assessments for Ukraine and the integration of digital technologies with practical data.

None.

None.

None.

## ACKNOWLEDGEMENTS

## FUNDING

## CONFLICT OF INTEREST

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## Сухі будівельні суміші з вторинною сировиною для реновації будівель: порівняльний аналіз властивостей і ефективності

**Анотація.** Метою дослідження була теоретична оцінка використання перероблених будівельних і промислових відходів у сухих реноваційних сумішах. Методологія охоплювала комплексний підхід до утилізації відходів у контексті сталого розвитку та визначенні перспектив для України. Встановлено, що часткова заміна цементу гранульованим доменним шлаком (25-50 %) знижує вуглецевий слід на 30-40 % без втрати міцності та довговічності, додавання перероблених заповнювачів (20-30 % від природного піску) забезпечує міцність  $\geq 10$  МПа при належному контролі гранулометрії та чистоти. Поєднання скла та шлаку підвищує щільність матриці й зменшує водопоглинання, але потребує контролю лужної реактивності. Виявлено, що аналіз життєвого циклу підтверджує зниження CO<sub>2</sub>-викидів на 20-40 % при використанні переробленої сировини, водночас значна економія первинних ресурсів зменшує тиск на довкілля та обсяги відходів. Використання методів математичного планування експерименту дозволяє швидше підбирати оптимальні рецептури, зменшуючи кількість експериментів у 8-10 разів. Натурні випробування у Португалії, Індії та Південно-Африканській Республіці підтвердили можливість практичного використання сумішей із вторинними матеріалами у штукатурних і мурувальних роботах. В Україні потенціал застосування таких технологій став значним з огляду на потреби післявоєнної відбудови та наявність великих обсягів будівельних і демонтажних відходів. Найперспективнішими рішеннями для реноваційних сумішей стали гранульований доменний шлак, класифіковані дрібні фракції (після очищення можуть замінити 20-30 % піску без втрати властивостей), комбінації гранульованого доменного шлаку та скляного порошку, склади, оптимізовані за допомогою машинного навчання. В Україні головними бар'єрами стали недостатній рівень контролю якості та слабка лабораторна база, однак регіональні виробництва сумішей здатні забезпечити ефективне використання відходів будівництва у відбудові. Практична значимість полягає у використанні результатів будівельними компаніями, виробниками матеріалів для екологічних сумішей і стандартів відновлення

**Ключові слова:** утилізація відходів; альтернативні в'язучі матеріали; довговічність розчинів; лабораторні випробування; польові випробування; стійкість до агресивного середовища; ресурсоефективність