RECONSTRUCTION OF POST-GENOCIDE GAZA WITH RECYCLED CONCRETE REINFORCED BY NANOTECHNOLOGY

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ABSTRACT

The Gaza Strip suffered massive infrastructure damage from the genocide, which resulted in millions of tons of building debris. The limited supply of new materials due to the blockade prompted the need for innovative and sustainable reconstruction solutions. This study presents a pure literature study on using recycled aggregate concrete enhanced with nanotechnology (e.g., nano-silica) to reconstruct post-genocide Gaza. The study showed that recycled aggregates from building ruins can replace up to 50% of natural aggregates without significantly decreasing concrete strength. The addition of nano-silica has been proven to improve the mechanical performance of recycled concrete, with an increase in compressive strength of up to about 20% compared to ordinary recycled concrete, and increasing durability resistance to chemical attacks. Using recycled materials and nano-silica also supports the cement industry's reduction of construction waste and carbon emissions, which aligns with sustainability principles. Nonetheless, there are challenges in standardizing the quality of recycled aggregates and applying new technologies in gaza areas. This article discusses the potential of nanotechnology in Gaza's reconstruction, its contribution to sustainability, the findings of recent studies in genocide areas, and the technical and policy challenges that must be overcome.

Keywords: Recycled Concrete; Nanotechnology; Nano-silica; Gaza Reconstruction; Sustainability

1. INTRODUCTION

The prolonged genocide in Gaza has resulted in severe infrastructure damage, leaving behind a large pile of building debris. For example, the 2014 genocide alone resulted in about 2.5 million tons of building rubble in Gaza(Al-mabhouh et al., 2021). After the 11-day attack in May 2021, it was reported that an additional ~200 thousand–300 thousand tons of construction debris would be managed(Linah Alsaafin & Amra, 2021). This situation is exacerbated by a blockade that restricts the entry of new construction materials, as more than 1,000 building materials are categorized as "dual-use" items prohibited from entering(Linah Alsaafin & Amra, 2021). As a result, Gazans are forced to have **"Extensive experience"** in recycling debris for development needs(Linah Alsaafin & Amra, 2021). This condition demands an innovative reconstruction approach that can make optimal use of local materials (rubble).

Globally, the construction industry is also facing pressure to be more sustainable(Chen et al., 2025). Conventional concrete production has a significant environmental impact; The cement industry, as the main component of concrete, accounts for ~8% of the world's total CO₂ emissions. In addition to carbon emissions, the construction sector generates >40% of global solid waste, mainly from building waste and demolition (Koh & Ho, 2006). Therefore, reusing construction waste is an essential part of the agenda in many countries(Koh & Ho, 2006). Several countries have implemented regulations encouraging the reuse of construction materials (Chen et al., 2025). The European Union, for example, is targeting high levels of recycling of building materials, and countries such as Japan and South Korea have integrated recycled concrete technology in infrastructure projects (highways and multi-storey buildings) to reduce reliance on depleting natural aggregates. This global trend shows an increasing focus on recycled material innovation as a sustainable development solution (Kurniasih et al., 2025).

Concrete with recycled aggregate concrete (*RAC*) offers opportunities to harness debris as a source of new building materials (Tommy et al., 2025). Studies show that recycled aggregates from scrap concrete can replace natural aggregates without sacrificing the mechanical qualities of concrete, provided the proportions and treatment are appropriate. In addition, various industrial wastes such as fly ash and slag can be utilized as cement substitutes, which not only lowers carbon emissions by ~30% but also increases the resistance of concrete to sulfate attack and reduces permeability(Ehsani et al., 2017). That is, the approach *circular* in construction – by recycling aggregates and utilizing waste as a substitute material – it has the potential to address two problems at once: material shortages and environmental impact.

However, the use of recycled aggregate concrete still faces various obstacles. The properties of recycled aggregates tend to vary depending on the source of the waste and the recycling method, so the consistency of quality is not guaranteed(Tommy et al., 2025). Compared to natural aggregates, recycled aggregates typically have higher water absorption and greater porosity due to old cement mortar attached. This can lower the *workability* of concrete mixtures and slightly reduce compressive strength and long-term durability, e.g., susceptible to reinforcement corrosion(Kurniasih et al., 2025). These technical obstacles must be overcome so recycled concrete can meet the required construction standards, especially for structural components.

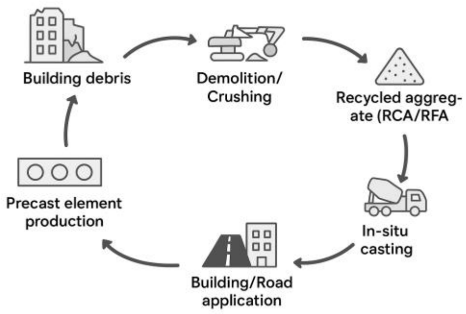

Figure 1. Gaza reconstruction scheme based on the use of debris with nano-silica

As material technology advances, one approach to improving the performance of recycled concrete is through **nanotechnology**. Nanomaterials such as nano-silica ($nSiO_2$) have shown promising results in enhancing concrete microstructures(Kurniasih et al., 2025; Tommy et al., 2025). Nano-silica is so small in particle size (~10–100 nm) that it can fill micropores and react with pozzolan calcium hydroxide, resulting in additional C-S-H gel in the interface transition zone (ITZ)(Chen et al., 2025). With this mechanism, adding nano-silica can improve the performance of recycled aggregate-based concrete. Previous studies have reported that nano-silica additives can significantly increase the compressive strength of recycled concrete and reduce its porosity. In fact, in the composition of RAC with 100% recycled aggregate, the addition of 3% nano-silica was recorded to increase the compressive strength by ~22% and flexural strength by ~25% compared to RAC without nano-silica (Ehsani et al., 2017). In addition to increasing strength, nano-silica modifications also improve the durability of concrete. (Chen et al., 2025) It found that nano-silica-modified recycled concrete retained 85% of its compressive strength after 56 days of exposure to sulfate solutions, while regular recycled concrete dropped to ~70%. These findings indicate the great potential of nanotechnology to close the performance gap between recycled concrete and conventional concrete.

Based on the above background, this article presents a comprehensive review of the latest research (last 5 years) on using nanotechnology-reinforced recycled concrete in the context of post-genocide reconstruction. The focus of the discussion includes: (1) the potential of nanotechnology (e.g., nano-silica) in improving the performance of environmentally friendly concrete based on recycled aggregates; (2) the role of recycled materials in supporting sustainability and waste reduction; (3) case studies and experiences of infrastructure reconstruction in conflict or post-disaster areas relevant to Gaza; and (4) technical and policy challenges in the implementation of this technology in genocide-affected areas. It is hoped that this review can provide a scientific basis for formulating an innovative, sustainable, and resilient Gaza reconstruction strategy.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

2.1 Recycled Aggregate Concrete : Potential and Characteristics

The use of recycled aggregate from building debris has become a popular research topic in an effort to create environmentally friendly concrete. Various global studies support the feasibility of recycled aggregate concrete as a substitute for conventional concrete. (Res et al., 2005) reports that recycled coarse aggregates can replace natural aggregates to a certain proportion without a significant decrease in the compressive strength of concrete. This success is generally achieved with a careful mixing strategy, such as limiting the percentage of recycled aggregates (e.g., 30–50%) or a combination of recycled aggregates and natural aggregates to obtain optimal gradation and density. In the context of post-genocide reconstruction, the abundant availability of concrete debris makes recycled aggregates a logical and economical material source. A post-genocide study in Syria showed that aggregates from the destruction of building rubble can be directly used in new concrete mixes, replacing up to 50% of natural coarse aggregates without sacrificing the structural performance of the concrete(Alex Brinded, 2023). The findings are particularly relevant for Gaza, which faces a similar situation, where thousands of destroyed buildings provide a stock of recyclable used concrete.

Materially, recycled aggregates generally come from old concrete fragments that still contain attached cement mortar. As a result, the physical properties of recycled aggregates differ from natural aggregates – lower density, higher water absorption, and rougher/more porous surfaces. This has an impact on the properties of the resulting concrete: *workability* tends to decrease and requires adjustment of moisture content or consumption *admixture* (e.g., superplasticizer) to achieve the same friction as regular concrete(Ash et al., 2022). The compressive strength of recycled concrete is often reported to be slightly lower than that of natural aggregate concrete, with a decrease of 5–15% depending on the percentage of substitution and quality of the recycled aggregate(Ash et al., 2022). Nonetheless, such strength is still acceptable for many structural applications, especially considering its environmental benefits. In addition, the long-term durability properties of recycled concrete are a concern: higher porosity has the potential to facilitate the penetration of aggressive substances (chloride ions, sulfates) that can accelerate reinforcement corrosion. Therefore, improving the quality of recycled aggregates through processing techniques (such as residue mortar cleaning, silica immersion, or carbonization) is being investigated to obtain more homogeneous quality recycled aggregates and better performance.

In terms of environment and sustainability, the use of recycled aggregates clearly brings benefits. First, the volume of construction waste disposed of in landfills is drastically reduced, reducing environmental impact and disposal costs(Armus et al., 2022; Ervianto, 2010). Second, the need for mining natural aggregates (stones, gravel, sand) is reduced, helping the conservation of natural resources that are increasingly limited. Third, recycled concrete's production process generally has a lower carbon footprint, especially when combined with supplemental cement materials (fly ash, slag) that reduce the use of Portland cement. These benefits align with circular economy initiatives and Sustainable Development Goals (SDGs) targets in the infrastructure sector. In other words, recycled concrete offers a green reconstruction approach particularly relevant for Gaza, where ecological pressures and new material limitations are a daily reality.

2.2 Nanotechnology to improve the performance of recycled concrete

Nanotechnology in construction materials mainly refers to using nanometer-scale particles to modify the microstructure and properties of materials(Ehsani et al., 2017; Koh & Ho, 2006). In the concrete context, nano-silica ($nSiO_2$) is one of the most researched and used nanomaterials. Nano-silica has a very high surface area and a significant chemical reactivity to calcium hydroxide ($Ca(OH)_2$), cement hydration products(Koh & Ho, 2006). Adding small amounts of nano-silica to the concrete mixture can accelerate the pozzolanic reaction and produce more calcium-silicate-hydrate (C-S-H) gel that fills the pores, making the concrete denser and stronger.

Various studies have shown the effectiveness of nano-silica in improving the quality of concrete, including concrete with recycled aggregates. (Ehsani et al., 2017) and other researchers report that adding $nSiO_2$ 1–5% by weight of cement can significantly increase the compressive strength of concrete, especially at its initial life, with an optimal dose of about 3–4% to strike a balance between increased strength and workability. Specifically on recycled concrete, (Rashwani et al., 2023), through a collaboration of researchers in the UK, Turkey, and Syria, found that adding nano-silica allows the use of 100% recycled aggregates in concrete with minimal performance degradation. With 3% nano-silica, the 100% recycled aggregate concrete actually experienced an increase in compressive strength of ~22.5% and flexural strength of ~25.6% compared to similar concrete without nano-silica(Momotaz et al., 2023; Nandhini & Karthikeyan, 2022). This increase is attributed to the improvement of the paste-aggregate transition zone; Nano-silica reduces micro-cavities and adheres new cement paste to the old aggregate surface more effectively.

In addition to improving mechanical properties, nano-silica contributes to recycled concrete's durability. (Chen et al., 2025) Conduct a multiscale investigation of the resistance of recycled concrete to sulfate attack by nano-silica immersion treatment on recycled aggregates. As a result, recycled concrete with nano-silica modification maintained 85% of its initial strength after exposure to a sulfate solution for 56 days, much better than untreated recycled concrete, whose strength remained ~70%. Nano-silica effectively closes capillary pores so that sulfate ions are less pervasive, and increases paste-aggregate bonds so that micro-cracks due to gypsum/ettringite expansion are reduced. Similar findings were reported in the context of resistance to chloride penetration and improvement of the waterproofing properties of concrete. Thus, integrating nano-silica can overcome some of the durability weaknesses inherent in recycled concrete.

In addition to nano-silica, other nanomaterials have the potential for concrete, such as nano-clay, nano-alumina, graphene oxide, and nano-cellulose fibers(Ervianto, 2010). Some studies suggest that combining nano-silica with other materials can produce synergistic effects. For example, combining $nSiO_2$ with microfibers (polypropylene, natural fibers) can improve recycled concrete's ductility and crack resistance (Ehsani et al., 2017). However, the selection of nanomaterials must consider availability, cost, and ease of application in the field. For the reconstruction scale in Gaza, nano-silica is regarded as the most prospective because it is already relatively common in the industry (available as a *Colloidal silica* or ultrafine silica fume) and the required dosage is small. With a dose of ~1–3% of the weight of cement, nano-silica can be integrated into concrete mixtures without drastically modifying equipment or procedures. This is important given the limited field conditions in Gaza; Technological solutions must be practical and adaptive to local resources.

Based on the above review, it can be hypothesized that the *post-genocide Gaza reconstruction approach with nano-silica-reinforced recycled aggregate concrete will be able to meet structural requirements while increasing sustainability compared to conventional methods*. This hypothesis is supported by the trend of cutting-edge research results that show that the performance of recycled concrete can be improved close to (or even surpass) conventional concrete through nanotechnology interventions. Furthermore, in the results and discussion section, this hypothesis is critically analyzed by compiling the relevant literature findings to evaluate the extent of empirical evidence supporting the concept in the real context of reconstruction in Gaza.

3. RESEARCH DESIGN METHOD

This research uses a qualitative literature study method by collecting and analyzing the latest scientific sources relevant to the topic. The literature search focused on articles in Scopus-indexed journals in the last five years (2019–2024), especially those that discuss recycled concrete, nanotechnology in concrete, post-genocide reconstruction, and sustainable materials. In addition, supporting documents and reports from international institutions are also used to enrich the empirical context in Gaza.

The search results obtained dozens of publications, which were then selected based on specific criteria. Approximately 30 sources were selected as the primary materials of the study, with priority given to *peer-reviewed journals* of international reputation. The selection criteria include three aspects: first, the up-to-date publication (maximum of the last five years); second, direct relevance to the research focus, e.g. experimental studies of recycled concrete with nano-silica or post-genocide reconstruction evaluations; and third, the level of credibility of sources, both in the form of reputable journals, international conference proceedings, and reports of trusted organizations. In particular, Indonesian publications are also considered to provide an overview of the relevant local context and regulations.

The content analysis stage is carried out by examining the content of each selected source in depth. This analysis aims to identify key findings, methods, and conclusions related to the research topic. The analysis process was carried out thematically by grouping information into central themes, including the performance of recycled concrete, quality improvement techniques through nanotechnology, sustainability impacts, case studies of post-genocide reconstruction, and implementation challenges in the field. This thematic approach facilitates the preparation of a more comprehensive cross-study synthesis and drawing of common threads.

Based on the results of the literature analysis, this study compiled a synthesis to answer the research questions. Quantitative data such as the percentage increase in concrete strength, aggregate substitution limit, or amount of construction waste were analyzed descriptively-comparatively between studies. Meanwhile, qualitative data on implementation challenges, field conditions, and policy recommendations were analyzed narratively. From the synthesis results, the central hypothesis or argument underlying the discussion in the next section is then formulated.

Validation is carried out by cross-checking between sources to maintain the validity of the findings. Important information, such as the performance of nano-silica in recycled concrete, was compared with several studies to ensure consistency of results. Similarly, empirical data on conditions in Gaza, such as the volume of post-genocide debris or blockade policies, are verified through reliable news reports and official documents of international institutions.

With this methodological approach, this study seeks to maintain objectivity and wide information coverage. However, as a pure literature study, this study has limitations, especially related to the reliance on the availability of data from previous research and the potential for publication bias. Even so, strict selection and cross-validation steps are sought to minimize these limitations. In the end, the study results are presented in the form of a scientific narrative complemented by the author's interpretation of the implications for reconstruction efforts in Gaza.

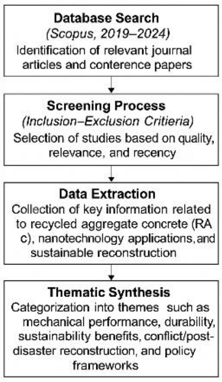

Figure 2. Research Methods

4. RESULTS AND DISCUSSION

4.1 Improved Performance of Recycled Concrete with Nano-Silica

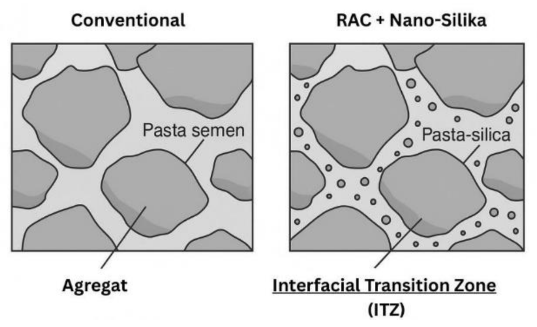

Figure 2. Schematic SEM Image of Conventional Concrete VS RAC+ Nano-Silica

Literature studies corroborate the suspicion that the integration of nanotechnology can significantly improve the quality of recycled aggregate concrete (Koh & Ho, 2006; Kurniasih et al., 2025; Tommy et al., 2025). In general, without special modifications, concrete with recycled aggregates tends to experience a slight decrease in compressive strength and modulus of elasticity compared to standard concrete. For example, replacing 50% of natural aggregates with recycled aggregates can reduce compressive strength by about 5–10%(Coffetti et al., 2022; Firmawan, 2007). However, this decline can be overcome through material engineering, one of which is by adding nano-silica to the mixture. Nano-silica reacts fast, binding *Ca(OH)_2* free to become C-S-H and fill micropores, which results in a denser and stronger cement paste structure(Koh & Ho, 2006). Experimental test results (Ehsani et al., 2017) show that recycled concrete with 3% nano-silica has a compressive strength 20–25% higher than recycled concrete without nano-silica at 28 days of age. This increase is even more pronounced in the bending and tensile strength, indicating significant improvements in the paste-aggregate's bonding strength and the concrete matrix's toughness (Koh & Ho, 2006).

In addition to strengthening, nano-silica also acts as an ultra-fine filler, which reduces the total porosity of concrete. As a result, nano-modified recycled concrete has a lower permeability to water and pollutants(Tommy et al., 2025). This was proven in durability testing: recycled concrete + nano-silica was able to resist sulfate attack better, with a residual compressive strength of 85% after 2 months of sulfate submersion, compared to ~70% in regular recycled concrete(Chen et al., 2025). Similarly, the decrease in chloride penetration rate and oxygen diffusion was recorded as lower, which means the correlation potential of reinforcement can be suppressed. In practical terms, this increased durability is essential for structures in Gaza exposed to marine environments (corrosive salty air) and may undergo limited maintenance. With low-porous concrete and chemical aggression resistance, the service life of the infrastructure can be extended.

Last but not least, nano-silica additives also have a positive impact on the *workability* and homogeneity of recycled concrete. Nano-silica particles, especially in colloidal form, can function similarly to mineral admixtures such as silica fume but with a faster effect(Nugraha, 2021; Rashwani et al., 2023). The study found that the combination of superplasticizers and colloid nano-silica was able to increase the slump of recycled concrete while still increasing compressive strength(Noorfauzi et al., 2025). This is because nano-silica optimizes the granulometry of cement paste and prevents segregation of recycled aggregates that are generally rougher on the surface. In other words, nano-silica helps to *compatibilize* between the new cement paste and the recycled aggregate, resulting in a more cohesive mixture. Of course, the dose of nano-silica needs to be optimized; An overdose (>5%) can lead to the agglomeration of nanoparticles and decrease the elasticity or cause ineffective excess gel pores. However, the low dose range of 1–3% has been consistently reported to be safe and effective in improving almost all aspects of recycled concrete performance (Coal & Cinderella, 2025).

Overall, the literature supports that the technical limitations of recycled concrete can be overcome through nano-silica interventions. The practical implication is that building reconstruction in Gaza can utilize recycled concrete without doubting its strength or durability, provided that the mixed formulation includes the right nanomaterials. This innovation answers the general concerns of engineers about the reliability of recycled concrete; The final product is claimed to be as strong and reliable as traditional concrete. Thus, nanotechnology opens up opportunities for the full utilization of debris as a source of quality construction materials in Gaza.

4.2 Contribution to Sustainability and Waste Use

Using nano-reinforced recycled concrete in Gaza is not only a solution to the problem of material shortages, but also in line with the principles of sustainable development. First, from an environmental perspective, this initiative directly reduces the post-genocide debris pile that must be treated or disposed of. Instead of being waste, concrete debris is diverted into a resource. This recycling cycle lowers the burden of solid waste disposal – a critical aspect given that Gaza is a densely populated area with limited landfill(Articles et al., 2025). Second, substituting natural aggregates with recycled aggregates reduces the need for new mining. Large-scale extraction of sand and gravel in the Middle East region can cause damage to coastal and river ecosystems. By utilizing used aggregates, environmental exploitation pressures can be reduced. Third, reducing the use of Portland cement can be achieved by utilizing *supplementary cementitious materials* (SCM) such as fly ash, slag, or even fine debris powder as cement filler(Coffetti et al., 2022). The combination of nano-silica and SCM technology has been studied to reduce the cement factor in the mixture without sacrificing strength, thus reducing carbon emissions from cement production. This step is crucial considering the issue of climate change and the high carbon footprint of conventional building materials.

In Gaza, the sustainability aspect also has a socio-economic dimension. Reconstruction projects that utilize local materials (rubble) will cut costs and dependence on imports. As a blockaded area, delivering materials from outside is often constrained or expensive. Recycled concrete offers *Standalone Solutions* By empowering the local recycling industry. Jobs in collecting, sorting, crushing, and mixing new concrete are created (Linah Alsaafin & Amra, 2021). Concrete examples: In Gaza, there have been initiatives to recycle rubble into gravel and to produce concrete blocks from the ruins of houses(Linah Alsaafin & Amra, 2021). With the support of technology (e.g., the use of mobile crushers, as is the practice in Syria(Alex Brinded, 2023), the production capacity of recycled materials can be improved. As a result, local communities gain economic benefits while reducing dependence on outside assistance for building materials.

Sustainability is also related to **Adaptation and Resilience** (resilience). Reusing debris to build demonstrates the ability of the people of Gaza to rise using existing resources, a principle of *Build Back Better*. In the long term, the application of this environmentally friendly concrete can be a pilot model for green reconstruction in other conflict areas. As it is said (Ehsani et al., 2017), this method can be replicated in any genocide or disaster site worldwide (Alex Brinded, 2023). Therefore, the successful implementation in Gaza has the potential to have a global exemplary impact on how to achieve sustainable and resilient infrastructure reconstruction simultaneously.

4.3 Case Studies of Reconstruction in Conflict and Disaster Areas

Valuable lessons can be learned from the study and experience of reconstruction in other regions facing massive destruction. In Syria, which has been ravaged by civil genocide for more than a decade, researchers conducted a trial using building rubble as a recycling aggregate. The results of a collaboration between the University of Sheffield (UK) and Syrian academics show that the new concrete made from 50% aggregate Syrian debris has the equivalent performance of standard concrete(Alex Brinded, 2023). In fact, the strength of such concrete is sufficient for structural applications, answering skepticism about the reliability of recycled concrete in conflict zones. The key to success in the Syrian study lies in: manual sorting of debris to separate unwanted materials, using mobile crushing machines on site, and optimized mix design (selection of water, cement, aggregate proportions) (Putri et al., 2014). A similar approach can be applied in Gaza by adjusting local conditions. For example, the UNDP program in Gaza has carried out a 2021 post-genocide debris clean-up project involving local contractors to break down used concrete into reusable aggregates(Abuhamed et al., 2023). The aggregate of the recycled products is reportedly used for road pavement work (sub-base) and the manufacture of simple construction concrete blocks(Abuhamed et al., 2023). This suggests that technically, the basic infrastructure can be immediately rebuilt by utilizing existing ruins.

In addition to conflict, the study of post-natural disasters is also relevant. After major earthquakes in several countries (e.g., Nepal 2015, Italy 2016), there was an impulse to use rubble as reconstruction material. The obstacles faced are similar, ensuring no harmful contamination in the debris, ensuring the consistency of the quality of the recycled aggregates, and adjusting the concrete design. In the case of the 2018 Lombok earthquake in Indonesia, local research found that debris aggregate can be used up to 30% in a mixture of mortar and non-structural concrete, although for structural concrete, it is still recommended to combine it with natural aggregates for safety. This provides the perspective that the optimal proportion of recycled aggregates can differ depending on the degree of damage to the material of origin(Articles et al., 2025; Coal & Sandalwood, 2025; Noorfauzi et al., 2025). In the context of Gaza, debris from buildings destroyed by explosions or collisions may be of different qualities (e.g., the initial strength of concrete varies, there are traces of explosives, etc.). Therefore, although the global literature provides a range of guidelines (50% or even 100% of the use of recycled aggregates is possible with modifications), local implementation needs to begin with comprehensive testing of Gaza materials.

From an institutional perspective, the Gaza case is unique because of political restrictions on material flows. The Gaza Reconstruction Mechanism (GRM), implemented after the 2014 conflict, for example, stipulates that imports of building materials such as cement and steel must go through special approvals to prevent abuse by militants(Barakat et al., 2018). Within this framework, efforts to produce self-sustaining construction materials inside Gaza are very strategic. Case studies show that after a genocide, multi-stakeholder coordination is required: local governments (Gaza's Ministry of Public Works and Housing) lead damage assessments and planning, international agencies (UNDP, donor agencies) provide technical assistance and funding, and local private sectors are involved in field executions(Abuhamed et al., 2023). Similar partnerships will also be needed for nano-recycled concrete technology. For example, funding may be required for the procurement of adequate quantities of nano-silica additives, training of local workers in new mixing technologies, and quality monitoring by local academic institutions (e.g., the Islamic University of Gaza has been involved in local materials research (Momotaz et al., 2023).

In general, experiences in various places confirm that reconstruction based on recycled materials is not just a scientific concept, but has been implemented on a limited scale with promising results. The key to success lies in adapting technology to the local context, institutional support, and quality assurance. Gaza has unique challenges, but also advantages: the spirit of independence of its people and the international community's support for reconstruction. By learning from other case studies, Gaza can develop its effective reconstruction model.

4.4 Technical and Policy Challenges in Implementation

Despite its potential, applying nano-reinforced recycled concrete technology in Gaza is not free from various challenges. The main technical challenges relate to **Quality standards**. The construction industry is usually guided by strict material standards (e.g., ASTM, BS, SNI), while local Palestinian standards may not yet cover recycled aggregates. Adjustments to technical specifications are required to accept recycled concrete as a structural material. Intensive laboratory testing must ensure parameters such as compressive strength, modulus of elasticity, shrinkage, and creep of recycled + nano concrete meet the building design requirements.

Furthermore, the scale of production of recycled aggregates is also challenging: it requires adequate debris crushing capacity and process consistency to produce aggregates with uniform gradation and cleanliness. If the quality of the aggregate batch fluctuates, the concrete yield will also vary. For this reason, standardization of the recycling process (from sorting, cleaning of residual mortar, to mixing techniques) is crucial(Abuhamed et al., 2023; Articles et al., 2025; Putri et al., 2014). Nano-silica technology itself needs to be controlled in its use; The nano-silica mixture must be homogeneous so that clumps do not occur. On the other hand, the availability of nano-silica in Gaza may be limited, so it must be imported or produced on a small scale (e.g., through silica extraction from local sand or glass waste, where possible).

The next challenge is the policy and regulatory aspect. Gaza is in a complex political situation that affects every development project. The blockade that lasted more than 15 years led to limited access to raw materials and heavy equipment(Linah Alsaafin & Amra, 2021). A breakthrough policy is needed so that recycled materials and nanoadditives can be recognized as vital components of reconstruction, and their procurement is facilitated. Local governments and international institutions need to formulate guidelines or *protocols* for the use of recycled aggregates in the field, including safety guidelines (e.g., ensuring debris is free from UXO/unexploded bombs)(Al-mabhouh et al., 2021) and environmental sustainability (management of dust and non-concrete waste). Policy incentives can be considered, for example, the provision of subsidies or funding assistance for contractors who use a high percentage of recycled materials, or ease of licensing for debris recycling business units. Building regulations should ideally be adjusted to accommodate these material innovations, so that engineers feel legally confident in applying them.

Funding and economic aspects are also a challenge. New technologies often face higher upfront costs. Although the use of debris reduces the cost of the aggregate purchase, there are additional costs for the recycling process (energy to crush concrete, sorting labor) and the purchase of nano-silica. Economic *feasibility studies* are needed to ensure that these solutions remain cost-effective compared to traditional options (e.g., waiting for an outside supply of materials). In

the long run, if the scale of production of recycled materials increases, the cost per unit will decrease. The key is to get through the initial transition phase. International donor support could be allocated to procuring shredders, constructing mini-recycling plants, or developing nano-silica stocks. The *public-private partnership approach* could also be explored, given that Gaza's reconstruction has attracted global attention and involved many stakeholders.
Lastly, the challenge of knowledge and acceptance. Local engineers, contractors, and workers may not be familiar with recycled concrete technology, let alone nano-silica. Socialization and training on this new material's production and testing procedures are needed. Local universities can play a role in education and quality monitoring. For example, a civil engineering laboratory at a local university may be appointed to periodically test the quality of recycled aggregates and mass-produced concrete, to maintain standards. The public must also be assured of the safety and reliability of buildings built from "used materials". An information campaign that says recycled + nanomaterials are not "second class" but of equal quality to conventional materials will help public acceptance. The support of community leaders and testimonials of the success of the pilot project can increase trust.
Facing the above challenges, the implementation strategy must be holistic. It needs a clear protocol from upstream (debris processing) to downstream (concrete production and construction). Regarding policy, it is necessary to have a regulatory framework and incentives that encourage this innovation. And socially, educational collaboration is needed to form local capabilities. With careful planning, these obstacles can be overcome one by one. The many obstacles underscore the urgency of innovation: the extraordinary situation in Gaza requires extraordinary solutions, in which recycled concrete, using nanotechnology, can be one of the answers.

5. CONCLUSION

The study confirms that the post-genocide reconstruction of the Gaza Strip can be effectively supported by the use of recycled concrete reinforced with nanotechnology. The use of recycled aggregates from building debris in Gaza has the potential to reduce dependence on imported materials and, at the same time, address the problem of post-genocide construction waste buildup. The results of the study show that the main obstacles of recycled concrete – such as a slight decrease in strength and durability due to higher porosity – can be overcome through the addition of nano-silica as a modifying material. Nano-silica has been shown to improve compressive strength, improve the density of microstructures, and improve the resistance of recycled concrete to environmental degradation. Thus, the quality of recycled aggregate-based concrete can be close to regular concrete, meeting the standards for structural applications.
In terms of sustainability, this approach is in line with the principles of circular economy and green development. Carbon emissions can be reduced by reducing the use of cement and new materials, while waste waste is diverted into valuable construction products. In the context of Gaza experiencing a blockade, material self-sufficiency through recycling is a strategic solution to accelerate reconstruction without waiting for external supplies. Case studies in Syria and other regions reinforce the evidence that this technique is feasible to apply in the field of

conflict, as long as it is supported by good quality management and monitoring.

Of course, the implementation of nano-recycled concrete in Gaza requires careful planning. Technical challenges (quality standards, production processes) and policies (regulations, licensing, funding support) must be anticipated from an early stage. It takes collaboration between local governments, donor agencies, the scientific community, and the local private sector to realize the infrastructure for the production of recycled materials and their distribution to construction projects. A pilot project on a limited scale could be a wise first step in evaluating the performance of nanotechnology recycled concrete in real conditions in Gaza while building public trust.

This technology offers a middle ground to meet urgent development needs while addressing sustainability challenges. With commitment and innovation, Gaza can be rebuilt greener, more independent, and more resilient for the future.

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