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The phoenix of reconstruction: A review of concrete rubble recycling for post-war urban rebuilding

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Abstract

In addition to destroying buildings and lives, wars also leave behind tons of debris that make life difficult to rebuild. Thus, on the second day following a conflict, it is absolutely necessary to use this debris for reconstruction. This goes beyond simply turning debris into a new resource; it also includes the sense of significance that comes with reconstructing their homelands from their ruins. In order to highlight encouraging experiences with using rubble from destroyed buildings, this study reviews a variety of research. Additionally, it highlights research on recycling rubble, examining the characteristics of recycled rubble and emerging technologies in this area. It also looks at the difficulties in making use of the findings of this study and the possibility of putting them into practice. For those looking to provide aid to regions affected by natural disasters and conflicts, the combined efforts of scientific research and their application may be a winning card. Therefore, in order to recover rapidly, reconstruction efforts must start with the findings of scientific research.

1. Introduction

Wars and conflicts create real environments of destruction, causing severe damage to the urban environment, as their impact extends to the destruction of buildings and infrastructure [1]. This destruction will generate tons of rubble, which could be a new resource for reconstruction. Using this rubble as authentic materials can preserve the identity of traditional architecture [2]. Using this rubble is a viable option [3], as the rubble resulting from destroyed buildings includes materials that can be reused and recycled for reconstruction [4]. This rubble constitutes important sources of materials that can be used in reconstruction and will have an economic impact if managed appropriately [5]. Since concrete aggregate is the most important part of this rubble, it is important to focus on recycling it [6]. The benefit of recycling building rubble is not limited to exploiting it as a new resource, but it also contributes to preserving the environment [7]. Post-disaster recovery creates an opportunity to coordinate reconstruction efforts with the achievement of sustainable development goals, resulting in building a safe and low-carbon environment [8]. If this rubble is left unexploited, it will become one of the biggest problems, especially in war and conflict zones due to the impact and weakness of the economic system in these areas, so proper management is what turns these rubbles into alternatives to natural resources [9]. Since sustainable development has become a requirement in most industries, recycling will be the most important in reducing waste [10]. The reconstruction of cities should not be done randomly, as it requires a methodology that is compatible with the recycling of building rubble. This will lead to reducing the environmental impact and also has an important economic role. Benefiting from previous experiences in this field is important. During the crisis created by World War II, the concrete of destroyed buildings provided an important building material [11]. With the passage of time, the process of recycling concrete increases in importance and has a place in various standards [12]. The importance of benefiting from recycling rubble ranges from its use in filling general blocks to building roads, all the way to producing concrete of satisfactory quality [4]. Therefore, it has become clear that we must replace the concept of the end of the material's useful life by reusing and reclaiming it to give satisfactory results. This is what the circular economy theory has adopted, which views waste as new resources that can be used and not as a problem that must be disposed of [13]. In general, the culture of using recycled aggregate varies between countries around the world. Figure 1 gives an impression of how the use of recycled aggregate varies.

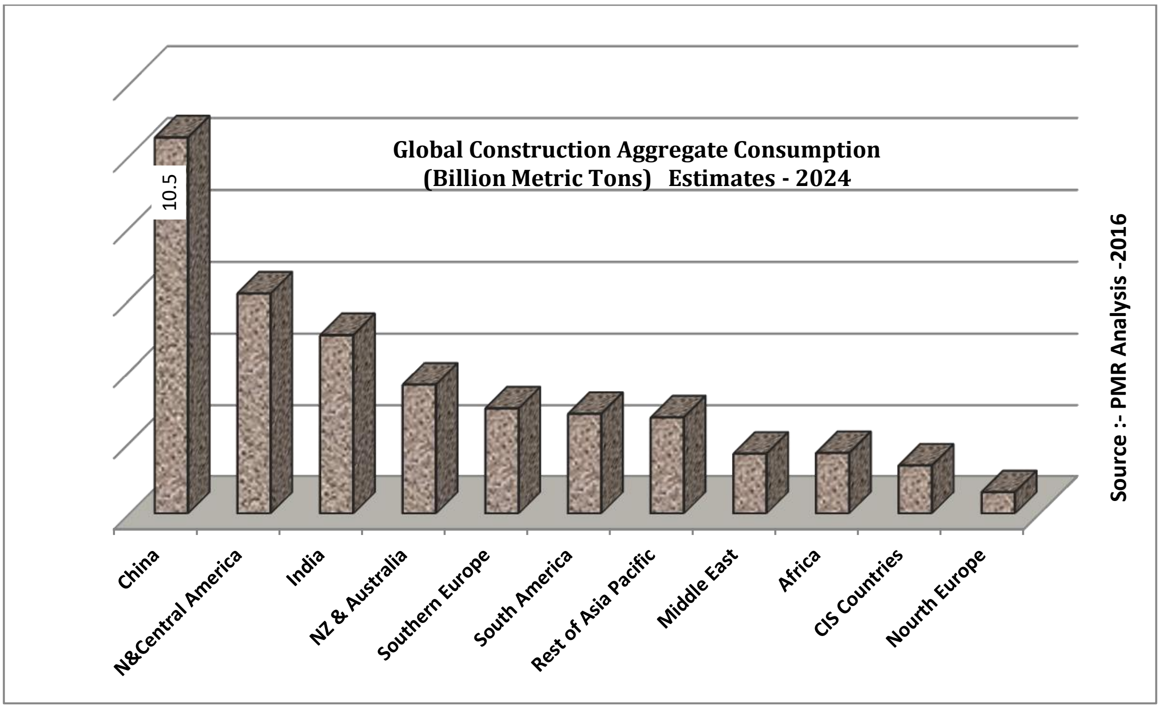


Fig. 1. Global consumption of recycled aggregate (by region) Adapted from V.W.Y. Tam et al [14].

Existing studies on the recycling of demolished building rubble reveal several gaps that limit its wider application in post-conflict reconstruction. Research has not distinguished between fully and partially destroyed buildings, making it difficult to accurately assess the behavior of rubble from different types of damage. Moreover, while various techniques have been proposed to enhance the properties of recycled materials, their practical applicability to specific structures and their economic feasibility remain unclear. Most investigations are also restricted to short-term experimental evaluations, leaving the long-term performance of recycled rubble over the actual lifespan of structures largely unknown. In addition, there is still no standardized international framework for the reuse of building debris, despite the increasing global demand for sustainable reconstruction in war-affected regions.

This study provides a review of research on war-affected areas and examines the success of recycling building rubble through various experiments. It highlights the results of scientific studies on concrete aggregate recycling, addressing both the properties of recycled aggregate and the techniques developed to improve its quality. The discussion also extends to the applicability of these findings to rubble from war zones, while outlining the environmental and economic benefits of recycling, as well as the challenges encountered in the process.

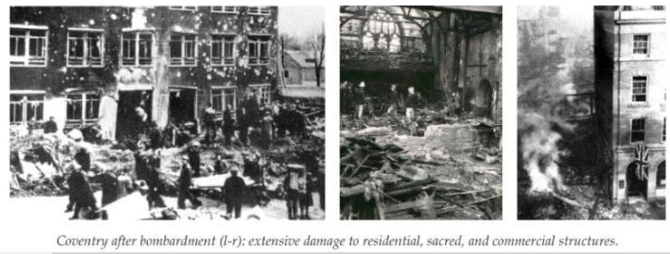
The scope of this review is defined through the categorization of the selected studies into two main thematic groups. The first addresses the environmental and economic aspects, including the impact of recycling on the environment and the potential economic benefits within frameworks such as the circular economy. The second focuses on technical aspects, encompassing the properties of recycled aggregate, the technologies developed to enhance these properties, and the specific challenges associated with recycling war debris. This categorization provides a comprehensive framework for understanding both the opportunities and the limitations of recycling war remnants and construction and demolition waste in the context of sustainable reconstruction.

2. Field studies and real-world applications of concrete waste recycling in conflict zones

Several cities have implemented reconstruction strategies that utilize debris from destroyed buildings. For instance, the Gaza Strip suffered repeated conflicts between 2008 and 2021, resulting in the creation of large quantities of debris. In May 2021, over 370,000 tons of debris were managed through coordinated efforts that included safe removal, sorting, and recycling. Given Gaza's geographic isolation and blockade, the availability of raw construction materials is extremely limited, making local recycling not only a practical solution but also an economically necessary one. Concrete rubble was used to rehabilitate roads and protect the coast. These efforts created new resources from building rubble and also had a positive impact on the city's economy through the creation of new job opportunities [15]. It will be crucial to adopt a circularity-based approach to debris management to the greatest extent feasible given the limited space available for disposing of debris within Gaza's small area as well as the lack of building and quarrying materials [16].

European experiences in the post-conflict period, although historically prevalent, offer lessons for contemporary applications. In Warsaw, following World War II, it was estimated that the amount of rubble scattered across the city reached 20 million cubic meters. As Eugeniusz Olszewski observed in Skarpa Warszawska, 'two million wagons would have to be loaded to carry it away, which was 20 times more than the total pre-war annual import of any goods and raw materials into Warsaw.' This overwhelming volume of debris, combined with limited access to new construction materials, made recycling not only practical but geographically and economically inevitable. Crushed concrete was therefore widely reused to rebuild the city, turning waste into a vital local resource. Beyond its technical function, the act of reconstructing Warsaw from its own rubble carried symbolic weight: the material itself became a medium of memory and identity, transforming urban space into a testament of resilience and renewal [11].

The war on Berlin and the subsequent siege of the city between June 1948 and May 1949 led to a severe shortage of building materials, prompting authorities there to seek new ways to provide building materials. They manually sorted the demolition waste to find usable materials. Women at the time were responsible for recycling the rubble, and these women later became known as the "rubble women." This sorted rubble was used to build emergency housing. After all the massive destruction it suffered, Berlin emerged as a model for urban planning [1]. In Iraq, the first debris recycling center was established in Mosul, in collaboration with the Mosul Municipality, with support from Japan. Mosul suffered from an estimated 7-8 million tons of debris, particularly in the Old City on the banks of the Tigris River. Gary Lewis, Director of the Disaster and Conflict Response Branch at UNEP, said: “The results of laboratory tests of construction materials confirm that the recycled debris complies with Iraqi road design standards. This paves the way for incorporating circular economy principles into routine construction and demolition waste management in general, thus promoting a build-back-better approach to recovery from crises” [17]. Figure 2 shows war-affected areas characterized by extensive debris accumulation. Although the raw materials needed for concrete production are readily available in the Mosul area, recycling offers a practical approach to managing the massive amounts of debris. In particular, using recycled aggregate in road backfill is beneficial, as it reduces processing costs.



(a)

(b)

(c)

Fig. 2. (a) Coventry after the bombing (left to right): Shows the accumulation of war debris after extensive destruction of residential and commercial buildings [18] (b) Demolition process of attacked building in Gaza [15] (c) The effects of destruction and the accumulation of war rubble appear in the old city of Aleppo [19].

The field research and real-world examples discussed above show not only that recycling concrete waste in areas affected by conflict is feasible, but also the many advantages that this strategy can provide. The benefits of using recycled concrete aggregate in fully devastated areas, both economically and environmentally, are covered in the following section**.**

3. Environmental and economic advantages

3.1 Environmental benefits

There are several environmental advantages to using recycled construction and demolition waste (CDW), especially concrete aggregate, as recycled aggregate when making new concrete. These advantages include less use of natural resources, lower energy and emission levels, and less strain on landfills [20].
Furthermore, a life cycle assessment conducted in Hong Kong showed that recycling coarse aggregate from CDW can result in a 65% reduction in greenhouse gas emissions and a 58% reduction in non-renewable energy consumption, indicating the environmental importance of recycling concrete debris [21]. In another study, it was found that using recycled aggregate in new construction leads to a 15% -20% reduction in carbon dioxide emissions [22]

In a specific study examining the environmental benefits of using recycled concrete aggregate (RCA) in concrete production, 50% substitution resulted in an overall 31.3% reduction in environmental impact. Specifically, the raw material supply (A1) and transportation (A2) phases experienced reductions of 34.7% and 40.3%, respectively, while the concrete production phase (A3) was unaffected. This demonstrates that the use of recycled concrete has become a necessity to significantly reduce resource consumption and emissions in concrete manufacturing. Research [23]. The environmental impact of concrete recycling extends to water, where it limits or reduces river sand extraction. Excessive river sand extraction causes environmental damage, including watercourse changes, beach erosion, and lower water levels resulting from sand dredging [24].

3.2 Economic benefits

Any economic benefits from recycling rubble from destroyed buildings must fall within the framework of a circular economy. This economy is based on the principle of renewing natural resources through recycling, utilizing renewable energy sources, and reusing waste through recovery and recycling. This contrasts with the linear economy in the construction sector, which involves using natural resources to produce materials, products, and structures, followed by disposing of waste after buildings are demolished or dismantled. Concrete is currently the primary building material. Scientifically, "recycling" is defined as a system of organizational, economic, and technological measures that return production and consumption waste to a recurring economic cycle [25].

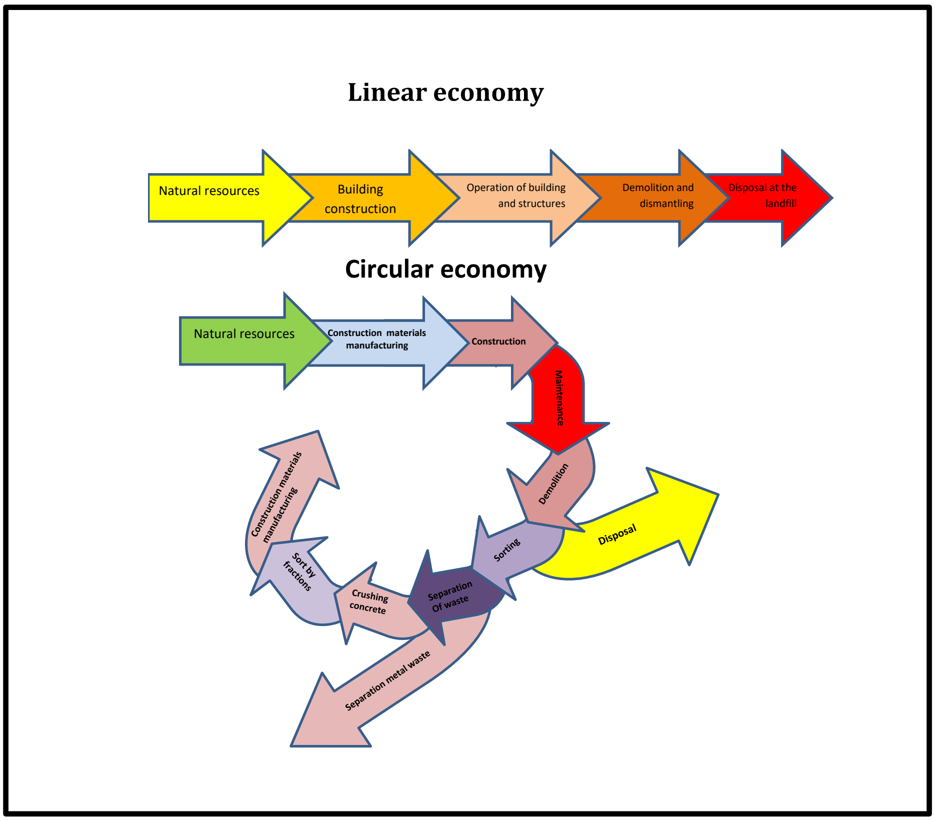


Fig. 3. Comparison between linear economy and circular economy Adapted from A. V. Graneva et al [25].

Figure 3 illustrates the difference between a linear economy and a circular economy in the construction sector. A linear economy follows a sequence of take, manufacture, use, and disposal," while a circular economy transforms this chain into a closed loop that returns materials to the cycle instead of sending them to landfills. The circular diagram representing the circular economy in the figure illustrates how materials are returned to the manufacturing process instead of being disposed of. The process begins with resources, followed by the manufacturing of construction materials, construction and maintenance. After demolition, the process continues with sorting, waste separation, concrete crushing, metal separation, fraction sorting, and manufacturing of construction materials, which then return to construction. The figure also demonstrates the possibility of disposing of a portion of the non-recyclable waste, while some remains unrecoverable. The use of recycled materials offers numerous economic advantages, particularly in terms of reducing costs associated with demolition waste removal and the delivery of new construction materials. In war zones, transportation often constitutes a significant portion of project costs [26].

These economic advantages are magnified if debris is separated and sorted at the source, where recyclable materials, including concrete, are sorted [27]. Recycling undoubtedly preserves natural resources and reduces the cost of producing new materials by reducing the costs of extracting new materials [28].

In the Gaza Strip, scientific results from debris management projects have confirmed their economic feasibility, as they have helped create new job opportunities and address the shortage of construction materials in the local market [7]. In construction waste management practices, the circular economy theory forms the theoretical basis for analyzing these practices [29]. This theory focuses on reducing waste disposal by reusing and recycling it, leading to its recovery as new materials [30]. Another economic advantage is that this rubble contains recyclable non-concrete materials, such as aluminum, steel, and wood. The sale of these materials reduces the overall cost of removing and crushing the rubble [31]. The use of recycled concrete aggregate offers clear economic and environmental advantages, but its practical application depends largely on knowledge of its mechanical and engineering properties. The following section discusses these properties, which determine the suitability of recycled aggregate for use in construction in areas destroyed by war. Extensive research on recycled aggregate has revealed these properties. These scientific findings can therefore be applied to aggregates manufactured from buildings destroyed by war, building on the results of previous studies in this field.

4. Mechanical and engineering properties of recycled aggregate

It is important to note from the results of scientific research on the properties of recycled aggregate that these properties are a true reflection of the properties of the original concrete aggregate. If the original concrete is of high quality, the recycled aggregate will also be of high quality. To gain a true understanding of the behavior of recycled aggregate, tests must be conducted at advanced ages to evaluate its long-term performance. The presence of bonded slurry poses a problem with recycled aggregate. This slurry consists of parts of the original concrete's natural aggregate and hardened cement slurry. Due to the high porosity of this bonded slurry, recycled aggregate absorbs a greater amount of water than natural aggregate. This bonded slurry must be removed using methods, treatments, and techniques. It is worth noting that there is currently no standard method for measuring its quantity in aggregate.

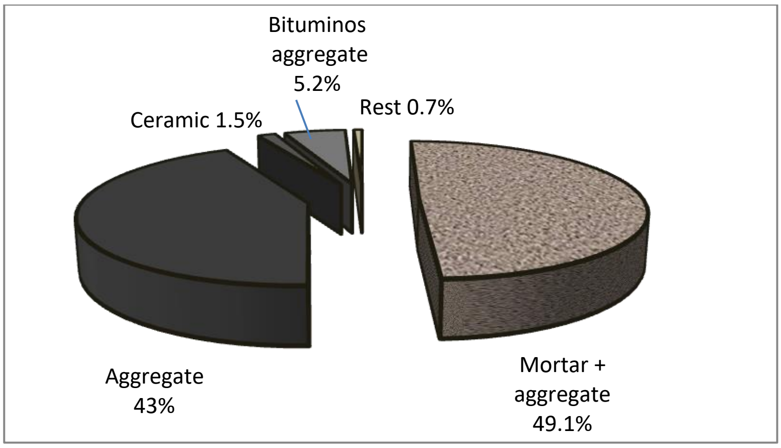


Fig. 4. Recycled concrete aggregates composition [32].

The figure 4 shows the components of the aggregate resulting from the demolition of concrete blocks. It is noted that it contains mortar and other impurities that must be removed by treatment methods to obtain high-quality aggregate that is similar in its properties to natural aggregate, because the presence of these materials with the aggregate directly and negatively affects the properties of recycled aggregate.

Modulus of Elasticity of Concrete: As the percentage of natural aggregate replaced by recycled aggregate increases, the modulus of elasticity of concrete exhibits a significant decrease. The relationship is inverse, with the average modulus of elasticity decreasing by 4%, 15%, and 23% at replacement ratios of 25%, 50%, and 100%, respectively [21], The reduced elasticity of concrete results in greater structural deformations in the short term [33].

Concrete containing recycled aggregate exhibits significantly higher drying shrinkage than concrete containing natural aggregate. The 90-day shrinkage of concrete made with recycled aggregate was approximately 55% higher than that of natural aggregate concrete [34]. This increased shrinkage may be due to internal shrinkage in the recycled aggregate or the reduced capacity of the recycled aggregate particles to contain compared to natural aggregate [35].

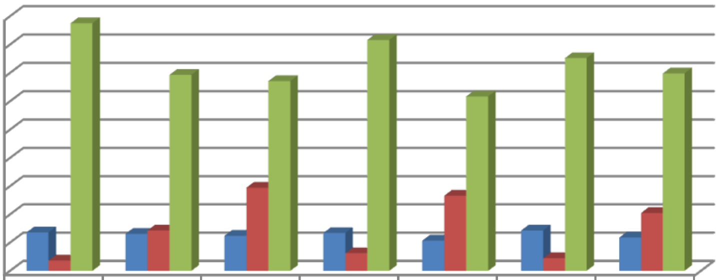
The flexural tensile strength of recycled aggregate concrete is notably lower than that of natural aggregate concrete due to the weaker nature of recycled aggregates. Although flexural strength generally correlates with compressive strength, the inferior quality of recycled aggregates significantly reduces flexural performance [36]. The hardened density of concrete made with recycled aggregates shows a noticeable reduction compared to concrete produced with natural aggregates [37]. This is due to the high porosity of the coarse aggregate due to the adhesion of porous mortar to the aggregate surface [38].

Compressive strength refers to the maximum stress that test specimens can withstand under uniaxial compression. The compressive strength of concrete containing recycled aggregate decreases with increasing content, compared to concrete made from natural aggregate [39] . Studies have shown that satisfactory results are achieved up to a 30% replacement rate of natural aggregate with recycled aggregate, aggregate considered satisfactory based on Indian standards [40].

The data confirm that recycled aggregates exhibit significantly higher water absorption compared to natural aggregates, primarily due to the presence of adhered cement mortar, which has greater porosity. Water absorption in natural aggregates typically ranges from 0% to 4%, whereas recycled aggregates show a wider range from 1.65% to 13.1%, with an average of 5.32% [32].

There are conflicting findings regarding the durability-related qualities of RAC, this is because the durability of concrete is linked to many of its properties, including porosity and abrasion. Since absorption and abrasion vary greatly in recycled concrete, the durability of recycled concrete also varies greatly. These variations in these properties are attributed to factors such as location, recycling methods, and the quality of the original materials. To improve the performance of recycled concrete (RCA), it is necessary to address deficiencies in its physical properties to increase durability [41]. this type of concrete shouldn't be used for structures exposed to harsh environmental conditions without the proper prior testing [42].

To maintain the performance and properties of concrete, natural aggregate must be partially replaced with recycled aggregate, not completely. However, there is no ideal percentage for this replacement, as the optimal percentage at which natural aggregate can be partially replaced with recycled aggregate varies. In the United Kingdom, research indicates that 20% of coarse natural aggregate can be replaced with coarse recycled aggregate, while in Australia, 30% of coarse natural aggregate can be replaced with coarse recycled aggregate, according to the guidelines there. In Germany, the German guidelines stipulate that up to 45% of coarse natural aggregate can be replaced with coarse recycled aggregate, but under certain conditions. These percentages are for coarse aggregate, and therefore fine aggregate also has different percentages depending on the regulations specific to each [43].Other research results can be viewed in the image below, which gives an idea of the properties of recycled aggregate compared to natural aggregate.



	NCA	RCA1	RCA2	NCA	RCA	NCA	RCA
	Vijayan et al.,2024			Stephen et al.,2019		Araf et al.,2018	
Spesific Gravity	2.72	2.62	2.48	2.68	2.14	2.86	2.36
Water absorption (%)	0.73	2.86	5.89	1.25	5.32	0.9	4.1
Density (g/cu.cm)	17.5	13.86	13.42	16.32	12.34	15.04	13.96

Fig.5. Physical characteristics of NCA and RCA, Adapted from P. Jagadesh et al [44].

Figure 5. compares recycled aggregate with natural aggregate in a number of physical properties. These results are consistent with those previously reported. The figure compares three studies, each conducted using recycled aggregate (RCA) compared to natural aggregate (NCA). The results of all three studies showed the same results: lower density and specific gravity of the recycled aggregate compared to natural aggregate, and a significant increase in water absorption of the recycled aggregate compared to natural aggregate. The values of the increases and decreases differed between the results of the three studies depending on the percentage of recycled aggregate, its type, and the test conditions.

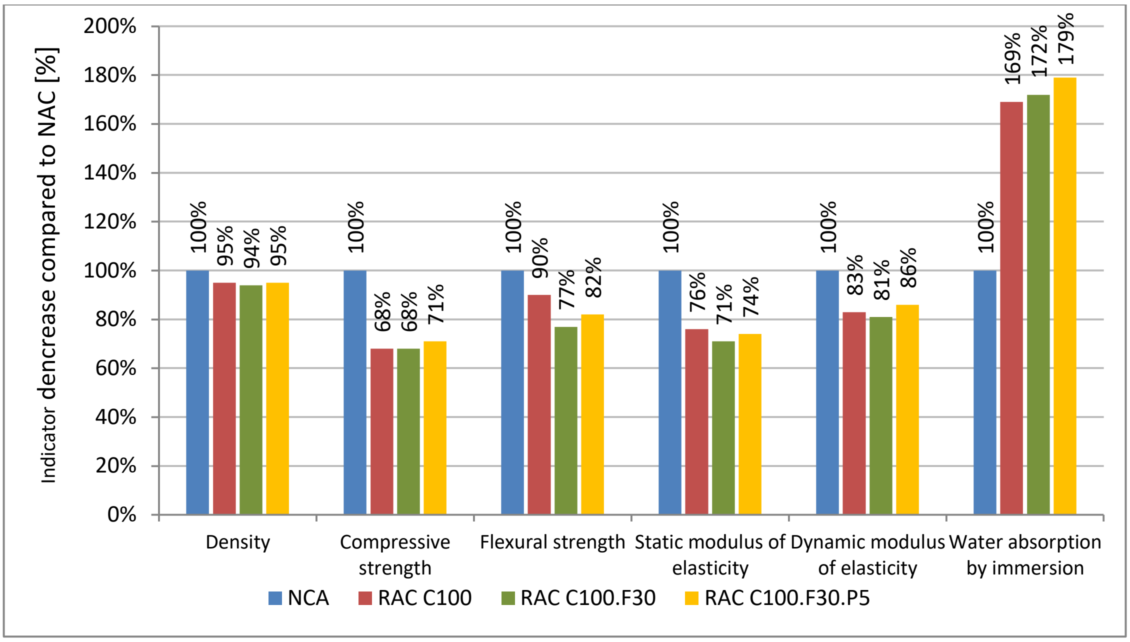


Fig .6. Mechanical properties of NAC and RAC concrete mixtures, Adapted from M. S. A. Alfitouri [45].

The figure 6 represents a comparison between concrete made from natural aggregate and concrete made with different replacement ratios of natural aggregate with recycled aggregate. Where NAC: Concrete made entirely of natural aggregate ,RAC C100: Concrete made of recycled aggregate made of natural sand and 100% recycled coarse aggregate ,RAC C100 F30: Concrete made of recycled aggregate comprising coarse aggregate (100% replacement) and fine aggregate (30% replacement) ,RAC C100 F30 %P5: Concrete made of recycled aggregate comprising coarse aggregate (100% replacement) and fine aggregate (30% replacement), with partial replacement of(OPC)with recycled cement (RCP) (5% replacement).

It is clear from the values in figure 6 decrease in the properties of recycled aggregate compared to natural aggregate, except for the water absorption property, which has increased compared to natural aggregate, this increase in this property and the decrease in the previous properties are all indicators of the necessity of carrying out treatments to improve the properties of recycled aggregate before using it to achieve satisfactory results similar to natural aggregate. A foundation for maximizing recycled aggregate's performance in construction applications is an understanding of its mechanical and engineering characteristics. The next section examines contemporary methods for improving these qualities and how their application can help with the efficient recycling of concrete waste in areas affected by conflict.

5. Techniques used to recycle concrete aggregate

Due to the increasing consumption of natural resources on planet Earth, there has been a need for the emergence of many technologies and treatments that are concerned with recycling natural resources so that they can be used again [46].
In the field of concrete recycling, various technologies and treatment methods have been developed to enhance the mechanical properties of recycled aggregates, aiming to achieve satisfactory performance in concrete applications. This is because the mechanical properties of recycled aggregate for concrete do not match those of natural aggregate, as they show a

decrease in most properties when compared to the properties of natural aggregate. These treatments and technologies can be used and their outcomes exploited in war and conflict areas, but their use necessitates the presence of international assistance that is concerned with these issues, and the international community's role is not restricted to relief efforts involving food and drink alone. However, because of the collapse of the economic situation in these areas, it must play a major role in intervening in all aspects of the step of reviving the homelands on the second day of the war. Foreign materials such as finishes, cladding, wood, dirt, steel, and plastic are frequently found in demolished concrete waste. It is necessary to remove impurities and crush the material with mechanical devices like jaw or impact crushers in order to turn this rubble into usable aggregate. Waste can be processed using any one of the three primary techniques—dry, wet, and thermal—alone or in combination. Using pre-soaked aggregates is sometimes advised because recycled aggregates have a tendency to absorb more water [47]. Among these technologies and treatments are the following:

5.1 densification treatments

One technique that can be used to improve the quality of RCA is densification treatments. For example, bacterial calcium carbonate bioprecipitation forms a protective layer that reduces the porosity of the aggregate by plugging the pores of the mortar adhering to the recycled aggregate, which stabilizes the carbon within the concrete aggregate. The calcium carbonate precipitates into the pore structure of the mortar and acts as a barrier, improving the durability of the concrete [48]. There are several methods for this technique, including Microbial-Induced Calcium Carbonate Precipitation (MICP) The environmental efficiency of the MICP method has made it a promising approach. By filling pores and microcracks in reinforced concrete, this technique uses bacteria to produce calcium carbonate ($CaCO_3$), which greatly lowers water absorption, boosts strength, and improves microstructure. Studies reveal that RCA treated with MICP exhibits a 20% to 40% decrease in water absorption. Furthermore, because MICP is inexpensive and works well with cementitious materials, it is regarded as a promising modification technique.

According to one study, MICP treatment enhanced adhesion strength, increased mass, and decreased RCA water absorption by up to 32.5%. XRD and SEM analyses verified that stable calcite deposits filled in cracks and pores, improving the structural integrity of RCA and qualifying it for use in structural concrete [49].

5.2 Heating and rubbing method (HRM)

Japan has developed an innovative Heating and Rubbing Method (HRM) technology to produce high-quality recycled aggregates. In this process, demolished concrete is heated to approximately 300°C, causing the cement paste to become brittle due to dehydration. The heated concrete is then placed in a mill, where mechanical abrasion removes the loosened cement paste from the surface of the aggregate. This temperature was found to be optimal, as high heating (up to 500°C) does not negatively affect the quality of the aggregate, as confirmed by studies analyzing changes in density and water absorption [50].

5.3 Transformation of destroyed sites into public spaces

The proposed strategy for post-conflict Aleppo focuses on the reuse of demolition debris through simple techniques such as direct reuse or basic rehabilitation, reducing the need for complex recycling processes. This approach enables the transformation of destroyed sites into public spaces and disaster risk management areas with efficient on-site waste management. This method prioritizes the sustainable use of debris that respects the city's historic urban fabric [19].

5.4 Building information modeling (BIM)
Reusing demolition waste in reconstruction offers significant environmental benefits and enhances building sustainability by reducing energy consumption and electricity costs. Using Building Information Modeling (BIM) technology to simulate reconstruction, this approach compares the energy performance of traditional materials with recycled alternatives derived from demolition waste. This method offers an innovative solution for sustainable reconstruction in post-conflict urban areas [9]. By accurately identifying and estimating deconstruction materials, BIM helps create customized demolition and waste management strategies. It also makes waste management plans more precise and timely. This increases recycling and reuse rates, reduces deconstruction and logistics expenses, and prevents poor management [51].

5.5 Polymer-based treatment
To improve recycled concrete aggregate's (RCA) reusability, an effective polymer-based treatment has been suggested. The properties of RCA showed significant improvements when silicon-based polymer treatments were used and compared with untreated RCA. One important improvement is the notable decrease in water absorption rates following treatment. The treated RCA is given water-repellent properties by the polymeric film that forms inside the pore network, which efficiently restricts water uptake. In alkaline environments, the film also exhibits strong resistance. The preparation of the polymer-based treatments is simple [52]. The results indicate that the compressive strength and water absorption capacity of recycled concrete are affected, directly or indirectly, by the polymer composition, concentration, and curing time. As shown in Figure 7 [53].

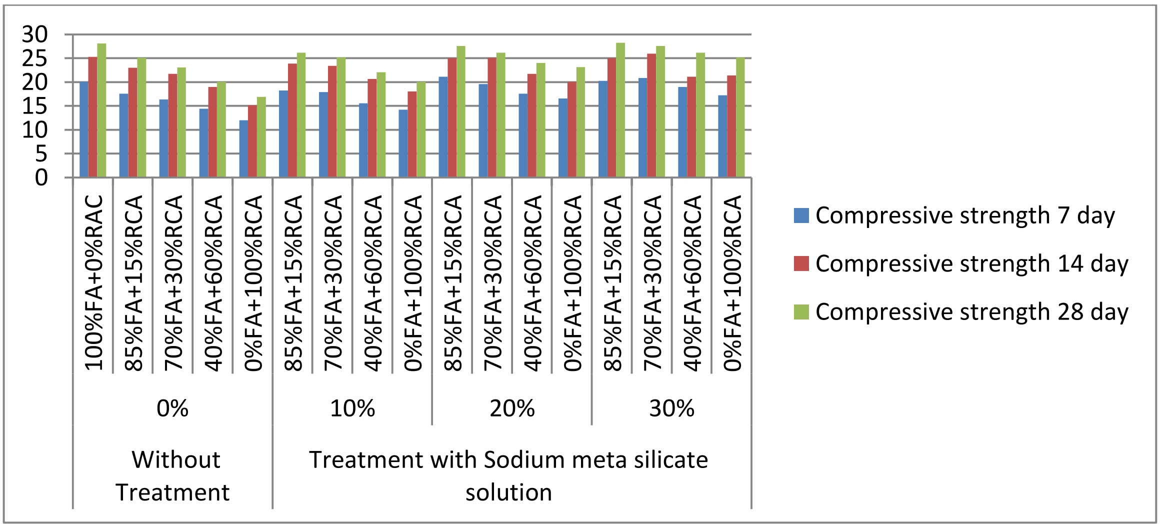


Fig. 7. Comparison of compressive strength of M25 casted with untreated aggregate and treated with sodium meatsilicate at 7, 14 and 28 days of curing Adapted from V. Spaeth et al [53].

5.6 Adhered mortar removal

The crushing process causes recycled aggregates to frequently have irregular shapes and sizes of particles, as well as changes in composition and surface textures, all of which have a substantial impact on their properties. Furthermore, the mechanical performance of recycled aggregates is lower than that of natural aggregates due to the presence of micro cracks in the adhered mortar and fractures within the original aggregates that occurred during crushing.

Removing the adhered mortar is a frequently used technique to improve the quality of recycled concrete aggregate (RCA). Remaining mortar can be effectively separated from the original aggregate particles using mechanical methods like ball milling and repeated crushing. Autogenous milling has also become a good substitute for removing surface contaminants.

Another method is ultrasonic water cleaning, which involves repeatedly rinsing until the water runs clear, signifying that mortar that has been weakened has been removed. Additionally, it has been demonstrated that chemical treatment with low-concentration hydrochloric acid (0.1 M and 0.5 M HCl) is effective in eliminating loosely bound particles and creating smoother aggregate surfaces [54].

A different combined technique was used in one study, involving mechanical, chemical, and thermal treatment. This multi-step procedure included immersion in HCl and H_2SO_4 solutions at different concentrations (1 M, 2 M, 4.5 M, and 5 M, where M denotes molarity) for 48 hours, as well as mechanical crushing using a Los Angeles test machine. After two hours of heating to 400 °C, the samples were left to cool. According to the study, the 2.5 M H_2SO_4 acid treatment produced the lowest water absorption [55]. While modern techniques for enhancing the properties of recycled concrete aggregate offer significant opportunities for sustainable reconstruction, their application in post-war cities is not without challenges. The following section examines the technical, economic, and logistical obstacles that must be addressed to ensure effective and safe recycling of rubble in regions devastated by conflict.

6. Challenges and obstacles in recycling rubble in post-war cities

One of the most significant challenges facing the recycling of rubble from buildings destroyed in war-torn cities is the hazardous nature of this rubble, given its potential to contain explosive materials [5].In Gaza, for example, test results showed that the concrete rubble left after the war contained unexploded ordnance and asbestos. These materials represent approximately 10% of the rubble and pose a real threat to human health. Therefore, removing these materials and storing them appropriately will reduce their danger [31]. In addition, the danger of building debris destroyed by bombs or missiles, which may contain radioactive material, is present. If the rubble from buildings is free of radioactivity, it can be used as recycled material in new concrete. Therefore, it is important to ensure that the rubble is free of radiation. This can be done by using a high-resolution gamma ray spectrometer to determine the elemental concentrations of radionuclides of thorium and uranium, specifically depleted uranium and potassium. If the rubble samples taken show a normal range of radioactivity for the specific radionuclides, the rubble can be considered reusable, and vice versa [56]**.**

The debris itself poses a safety risk and a physical barrier to access, which has significant effects on the return of internally displaced people and the provision of humanitarian aid. Physical harm can result from falling debris and unstable structures that could collapse, and health risks can arise from hazardous materials mixed in with the debris [16]. One of the key challenges is the properties of recycled aggregates, given that they contain old mortar, which is characterized by its adsorption capacity and poor mechanical and chemical properties. These properties affect the rheological behavior of concrete, reducing its strength and ductility while increasing its shrinkage [57]. Aggregate recycling efforts face numerous challenges, including the absence of comprehensive regulations, poor public awareness in the labor market about the potential use of recycled aggregate, and a lack of financial resources. These factors hinder the dissemination of knowledge about the feasibility of recycling practices and their environmental benefits, slowing progress toward sustainable waste management [58]. Therefore, the most significant challenges can be summarized as the absence of comprehensive national programs, guidelines, and policies on concrete recycling, as well as the lack of technical expertise in concrete recycling. [59]

7. Conclusions

The first and most crucial step in overcoming the difficulties of reconstruction is recycling concrete debris from damaged structures. War zones can benefit from the results of all concrete aggregate recycling initiatives in different nations. This is crucial for utilizing the results of scientific research and applying them during emergencies.
Since recycled concrete aggregate is directly related to the original concrete that was recycled, it is undeniable that the quality of recycled concrete aggregate varies widely. Poor recycled aggregate is a natural byproduct of poor original concrete, and vice versa.
The quality of recycled aggregate can be raised by utilizing new technologies. The difficulties that aggregate recycling faces must also be considered and should not be disregarded. These difficulties include the absence of uniform recycling procedures intended for use in conflict areas and the difficulties in utilizing this debris because it may contain dangerous substances from war remnants. It should be highlighted from the foregoing that recycling debris is a new compass for bringing life back to areas that have been devastated and a chance to turn debris into hope.
This study recommends the need to develop legislation and regulations specific to the process of recycling debris after disasters.

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