G-Tech : Jurnal Teknologi Terapan
Vol. 9, No. 4, October 2025, p. 1889-1900
E-ISSN: 2623-064X | P-ISSN: 2580-8737

Innovative Approaches to Post-Earthquake Reconstruction Material Evaluation for Healthy Simple Houses

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Article Information

Article History

Received : September 03, 2025
Revised : September 18, 2025
Published : October 04, 2025

***Keywords*:**

Post-earthquake reconstruction;
Healthy simple house;
Innovative design;
Mortar;
Sustainable housing.

ABSTRACT

Post-earthquake housing reconstruction is essential for accelerating community recovery and ensuring safer living conditions in disaster-prone regions. This study evaluates the potential of recycled rubble sand from demolished masonry walls as an acceptable aggregate replacement in mortar production. It explores its integration into the development of a Healthy Simple House (HSH) model for post-disaster housing reconstruction. Laboratory experiments were conducted in accordance with PUBI-1982 and SII 0052-80 standards to characterize material properties and assess mechanical performance. The results indicate that rubble sand exhibits a well-graded particle distribution, stable density values (SSD 2.48 g/cm³, bulk 2.35 g/cm³, apparent 2.71 g/cm³), and moderate water absorption (5.62%), with slight organic contamination. Compressive strength tests showed that mortars with a 1:3 cement-to-sand ratio reached approximately 24 MPa at 28 days, meeting structural requirements, while higher rubble proportions reduced strength, restricting their application to non-structural components. The incorporation of rubble sand into the HSH model highlights its role in sustainable reconstruction by reducing reliance on natural resources while ensuring safe, healthy, and affordable housing. The study concludes that recycled rubble sand can be effectively utilized as a partial aggregate substitute, providing practical guidance for post-disaster housing programs and informing policy development for environmentally friendly and resilient reconstruction strategies that contribute to community resilience.

INTRODUCTION

Earthquakes frequently cause severe damage to residential infrastructure, leaving communities vulnerable and in urgent need of safe and affordable housing solutions. The reconstruction of housing after such disasters is essential for restoring living conditions and plays a central role in accelerating social and economic recovery. In disaster-prone regions, particularly in developing countries, the challenge is to provide housing that combines structural resilience, affordability, and health-related considerations within limited resources and pressing timelines.

One of the key issues in post-disaster housing reconstruction is the availability of suitable construction materials. Traditional aggregates are often costly or scarce in the aftermath of an earthquake, while large volumes of rubble and debris accumulate from demolished buildings. This situation presents both a challenge and an opportunity: when properly processed and evaluated, rubble materials can be reused as alternative aggregates in mortar and concrete production. Such an approach supports sustainable construction practices and reduces environmental burdens associated with debris disposal.

Several studies have examined the utilization of construction and demolition waste in cement-based materials. Previous works have demonstrated that recycled coarse aggregates can be applied in concrete with acceptable mechanical performance, although strength reductions are often observed compared to natural aggregates (Naderpour et al., 2018; Pacheco-Torgal et al., 2013; Sato et al., 2007; Silva et al., 2017; Wu et al., 2022; Xie et al., 2022). More recent studies have also highlighted the potential of recycled fine aggregates, noting their influence on workability, density, and strength of mortar mixes (Boen et al., 2015; Evangelista & de Brito, 2007; Kou & Poon, 2012; Naderpour et al., 2018). However, using recycled rubble sand derived from demolished walls remains underexplored, particularly in its characterization and performance in mortar production.

Parallel to material innovation, research on post-disaster housing has emphasized rapid construction methods and structural resilience. For instance, lightweight prefabricated systems and modular housing designs have been widely proposed to ensure quick deployment and seismic safety (Boruah, 2022; Davidson et al., 2007; Johnson, 2007; Lehmann, 2012, 2013; Xiao et al., 2010). Nonetheless, studies often overlook health-oriented aspects such as ventilation, natural lighting, sanitation facilities, and cultural adaptability, essential for long-term sustainability and community acceptance.

Although numerous studies have advanced knowledge on recycled materials and emergency housing, integrating both dimensions recycled rubble sand utilization and healthy, simple housing design has received limited attention (Ballesteros et al., 2023; Hendrikz & Osman, 2022; Latka, 2017; Mahat et al., 2021; Mast, 2023; Nikolic, 2018; Nyakala et al., 2021; Okuta et al., 2024; Tahir, 2019). These gaps highlight the need for a holistic approach that addresses material sustainability and habitable design in post-earthquake reconstruction.

This study aims to fill these gaps by investigating recycled rubble sand from demolished walls as an acceptable aggregate replacement in mortar production and developing a Healthy Simple House (HSH) model. The material properties are evaluated according to national standards to ensure compliance with quality requirements and determine their suitability for structural and non-structural applications. This research offers a sustainable alternative for mortar production by integrating material innovation with housing reconstruction strategies. It contributes to developing affordable, resilient, context-appropriate housing solutions for post-earthquake recovery.

RESEARCH METHODS

Experimental Set-up and Measuring Equipment

The primary material used in this study was recycled rubble obtained from dismantled masonry walls of existing buildings. The rubble was collected from construction demolition sites, cleaned of debris and impurities, and processed into fine aggregate suitable for mortar production. The processing steps included crushing the rubble into smaller fragments and sieving it through standard mesh sizes to achieve the desired gradation for mortar mix preparation.

Portland Composite Cement (PCC) was used as the main binder, while the processed rubble served as fine aggregate in different mix ratios. Potable water was used for mixing and curing to ensure proper hydration and strength development. Using recycled rubble as aggregate reduces construction and demolition waste and offers an alternative, low-cost material that can potentially be applied in producing mortar specimens for healthy and straightforward housing construction.

Before specimen preparation, the recycled rubble aggregates were subjected to basic characterization tests. A sieve analysis was conducted to determine the particle size distribution and ensure that the gradation met the requirements for fine aggregate in mortar production. The sieving process allowed the removal of oversized particles and the adjustment of aggregate fractions to achieve a well-graded composition suitable for mortar mixes.

In addition, the specific gravity and water absorption of the recycled aggregates were measured using standard testing procedures. These properties are essential for assessing the quality and performance of aggregates in mortar production, particularly their influence on workability, density, and strength development. The characterization results provided the necessary input for designing mortar mixes with different ratios, ensuring the reliable use of recycled rubble as a substitute for conventional fine aggregate.

Figure 1. The material used in this study consists of rubble from demolished building walls in the Yogyakarta region

Figure 2. The gradation and specific gravity tests were conducted on recycled rubble obtained from the demolition of wall structures.

Cube specimens measuring 50 × 50 × 50 mm were prepared to investigate compressive strength. Five mortar mix proportions were designed with cement-to-aggregate ratios of 1:3, 1:4, 1:5, 1:6, and 1:8. For each mix ratio, four specimens were cast and tested at curing ages of 7, 14, and 28 days, resulting in a total of 45 specimens. The casting procedure followed standard laboratory practices, including mixing, molding, and compaction. After 24 hours of initial setting, all specimens were demolded and placed in a water-curing tank at room temperature until the specified testing age.

The compressive strength test was conducted using a Universal Testing Machine (UTM) with a maximum load capacity of 2000 kN. Each cube was placed centrally on the loading platform, and a constant loading rate was applied until specimen failure occurred. The maximum load recorded was used to calculate the compressive strength according to ASTM C109/C109M standards. Supplementary measuring equipment, such as a digital weighing balance, sieves for aggregate grading, and a water-curing tank, was also employed to ensure consistency and reliability of specimen preparation and testing.

This experimental setup allowed for a systematic evaluation of the effect of different cement-to-aggregate ratios and curing ages on the compressive strength development of rubble-based mortar. The results serve as the basis for assessing the feasibility of using recycled rubble material in the design of Healthy Simple Houses for post-earthquake reconstruction and estimating the corresponding construction cost plan.

Figure 3. Test cube specimens measuring 50 × 50 × 50 mm

Research Procedures and Data Analysis

The gradation of fine aggregate derived from recycled rubble of dismantled masonry walls must be analyzed to determine the particle size distribution. Gradation plays an important role in the proportioning process of mortar mixes and significantly influences the performance of mortar in wall construction. The analysis was carried out through a sieve analysis test. Per standard procedures, a set of sieves was arranged in descending order, starting from the largest to the smallest mesh size. The fine aggregate sample was placed in the sieve stack, followed by mechanical or manual shaking until no significant change in the retained mass was observed. After sieving, the retained mass on each sieve was weighed. The percentage of retained particles was calculated using Equation (1):

$$\%Retained = \frac{W_i}{W} \times 100\% \quad (1)$$

where:

W_i = weight of particles retained on sieve i (g)

W = total weight of the aggregate sample (g).

The percentage of passing particles was then determined using Equation (2):

$$Passing = 100\% - \%Retained \quad (2)$$

The obtained particle size distribution data were used to plot a gradation curve. From the curve, the value of Di (the particle diameter corresponding to i% passing) can be identified directly from the graph or by interpolation. The interpolation was performed using Equation (3):

$$D_i = X_1 + \frac{Y - Y_1}{Y_2 - Y_1}(X_2 - X_1) \quad (3)$$

where:

X_1 = sieve size corresponding to % passing lower than the target value

X_2 = sieve size corresponding to % passing higher than the target value

Y_1 = % passing lower than the target value

Y_2 = % passing higher than the target value

Y = desired % passing.

This analysis provides detailed information on the particle size distribution of fine aggregates derived from recycled masonry rubble. Understanding this gradation is essential for evaluating the physical characteristics of the material, which directly affect the density, homogeneity, and mechanical behavior of mortar when applied in construction.

The specific gravity of fine aggregates derived from masonry rubble is a key parameter representing the ratio between a given aggregate volume's mass and an equal volume of pure water. This property is an important indicator in analyzing fine aggregate characteristics and the overall quality of mortar. Specific gravity provides insights into the aggregate's density, porosity, and physical composition, which are crucial for determining the mix proportions of mortar.

The determination of specific gravity is carried out in the laboratory using the pycnometer method. The resulting value, denoted as the specific gravity of sediment (Gs), is subsequently applied in calculating mortar mix proportions to ensure the strength and durability of the mortar. The specific gravity of sediment can be calculated using Equation (4):

$$G_s = \frac{M_s}{(M_1 + M_{s)} - M_2} x\ K \tag{4}$$

Where:

G_s = Specific gravity of fine aggregates

M_s = mass of oven-dried fine aggregates (g)

M_1 = Mass of pycnometer + water (g)

M_2 = Mass of pycnometer + water + fine aggregates (g)

K = Temperature correction factor

The mortar specimens in this study were prepared with various cement-to-sand mix ratios of 1:3, 1:4, 1:5, 1:6, and 1:8. The compressive strength tests were carried out at the Structural Laboratory, Department of Civil and Environmental Engineering, Faculty of Engineering, Universitas Gadjah Mada. The tests were performed on cube specimens at curing ages of 7, 14, and 28 days. The compressive strength of the mortar was calculated using the following Equation (5).

$$\sigma_m = \frac{P_{max}}{A} \tag{5}$$

Where

σ_m : mortar compressive strength (MPa)

P_{max} : maximum compressive force (N)

A : cross-sectional area of the test specimen (mm^2)

RESULTS AND DISCUSSION

Characteristics of Rubble Material from Wall Demolition

The grain size distribution curve of the demolished wall rubble shows a well-graded material with particle sizes ranging from approximately 0.2 mm to 20 mm. The cumulative finer percentage increases steadily with grain size, reaching nearly 100% at around 20 mm. At a grain size of 0.2 mm, about 30% of the material passes, while at 1 mm, the passing percentage is close to 60%. The material exhibits a continuous gradation, with around 80% finer than 2 mm and more than 90% finer than 5 mm. This indicates that the processed rubble has a relatively uniform and compactable grading, making it suitable as a recycled aggregate for mortar or concrete applications. However, further tests such as specific gravity, water absorption, and mechanical strength are necessary to assess its construction material performance fully.

According to the Indonesian General Requirements for Building Materials 1982 (PUBI-1982), the fraction of material passing through a No. 200 sieve (0.074 mm) in sand should not exceed 5% by weight. This specification ensures that the sand has an adequate grain size distribution suitable for use in mortar or concrete mixtures, thereby maintaining the mechanical properties and durability of the resulting construction elements.

The sand samples were subjected to a visual color assessment to evaluate the presence of organic matter and potential contamination. The inspection revealed that the color of the sand deviated from the standard reference color. According to SII 0052-80, sand color should not be darker than the standard, as darker coloration generally indicates higher organic content, which can adversely affect cement-based materials' setting, strength development, and bonding properties.

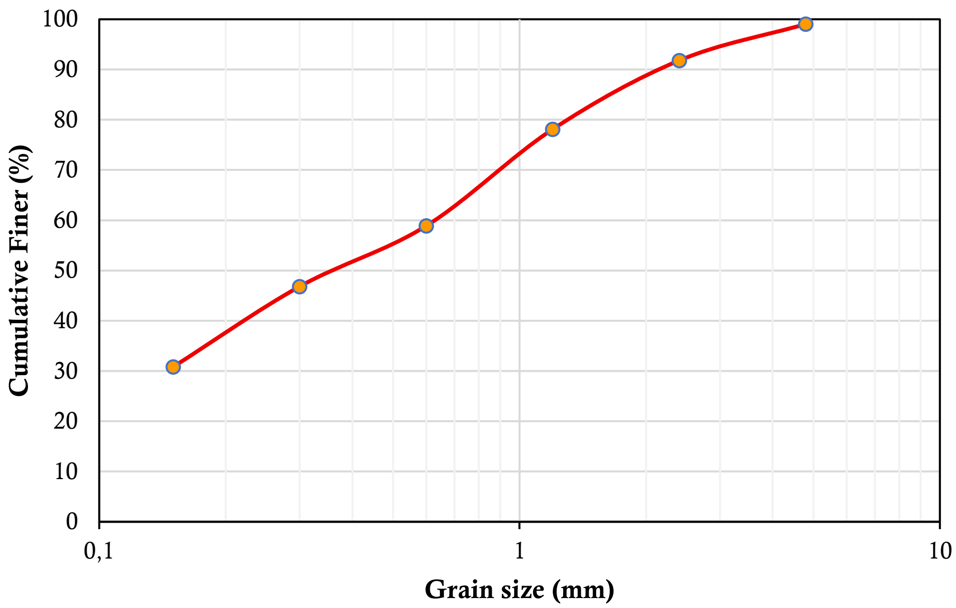

Figure 4. The material grain size distribution curve used in this study.

Quantitative analysis of the organic matter content confirmed that the sand exhibits a slightly darker color than the standard. This discrepancy is most likely attributable to the method of material preparation: the crushing process was conducted in an open environment, which exposed the sand to environmental contamination, including soil particles, plant residues, and other organic matter. Such contamination can influence the sand's physical and chemical properties, and consequently, its suitability for construction applications.

These findings highlight the importance of controlling the source and handling of recycled or crushed building materials to minimize contamination and ensure compliance with established standards. Further studies are recommended to assess the impact of the observed organic content on mortar or concrete performance, including strength, workability, and durability.

Based on the experimental results, the oven-dried surface-saturated sand weight (No. A) exhibited consistent values of 500 g for both specimens, indicating uniformity in the amount of sand used. In contrast, the absolute dry sand weight (No. B) had an average of 473.4 g, slightly lower than the surface-saturated weight, suggesting a relatively low natural moisture content in the sand. Pycnometer measurements yielded an average weight of pycnometer + water (No. C) of 1297.7 g and pycnometer + water + sand (No. D) of 1596.15 g, which were employed to calculate sand density.

Subsequently, specific gravity analysis showed that the saturated surface-dry density (SSD, No. E) averaged 2.48 g/cm³, indicating that the sand particles without air voids fall within standard ranges for construction sand (see Table 1). The bulk density (Sample F) averaged 2.35 g/cm³, lower due to the inclusion of intergranular voids. In comparison, the apparent density (No. G) averaged 2.71 g/cm³, reflecting the combined influence of particle volume and voids. Water absorption (No. H) averaged 5.62%, relatively low, indicating that the sand possesses low to moderate porosity, which would affect the water demand in mortar or concrete mixtures.

Figure 5. The results of the organic content showed that the color was slightly darker than the standard color.

The measured densities and water absorption indicate that the tested sand is sufficiently stable and suitable for light to moderate construction applications. The minimal variation among samples demonstrates material homogeneity, while the low water absorption suggests minimal clay or acceptable mineral content, making this sand appropriate for mortar mixes or wall casting (Nugroho & Takano, 2008; Satyarno, 2006).

Table 1. Results of Specific Gravity Examination of Rubble Material from Demolition of Building Walls

No	Description	Sample 1	Sample 2	Average
A	Weight of Over Dry Sample (gram)	500.00	500.00	500.00
B	Absolute Dry Sand Weight (gram)	473.50	473.30	473.40
C	Weight of Flask (Pycnometer) + Water (gram)	1313.70	1281.70	1297.70
D	Weight of Flask (Pycnometer) + Water + Sand (gram)	1612.50	1579.80	1596.15
E	Specific Gravity SSD Basis (gr/cm^3)	2.49	2.48	2.48
F	Specific Gravity Oven Dry Basis	2.35	2.34	2.35
G	Apparent Specific Gravity	2.71	2.70	2.71

No	Description	Sample 1	Sample 2	Average
H	Absorption (%)	5.60	5.64	5.62

Compressive Strength Test of Mortar Cast Specimens

The compressive strength test of mortar cast specimens was conducted by replacing natural sand with finely crushed rubble from demolished wall materials. This approach was intended to evaluate the feasibility of using construction and demolition waste as a sustainable alternative to conventional fine aggregates. Mortar specimens were prepared using different cement-to-sand ratios, namely 1:3, 1:4, 1:5, 1:6, and 1:8, and subsequently tested at curing ages of 7 days (see Figure 6), 14 days (see Figure 7), and 28 days (see Figure 8). The early test results indicated that the inclusion of rubble sand influenced the rate of strength development, particularly during the initial curing period. At 7 days, compressive strength values were relatively low, especially for mixtures with a smaller proportion of cement, highlighting the slower initial strength gain compared to mortars made with natural sand.

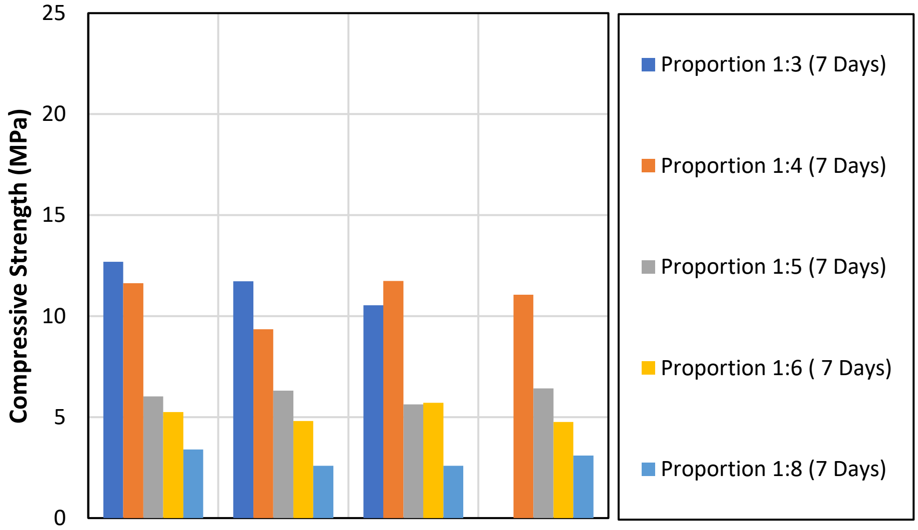

Figure 6. Compressive Strength Test Results with 7-Day Mortar Age

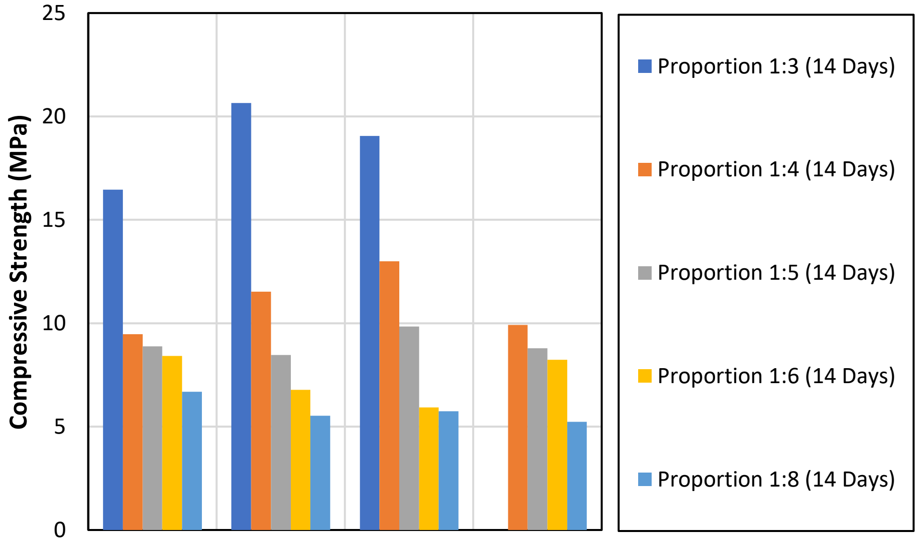

Figure 7. Compressive Strength Test Results with 14-Day Mortar Age

As curing progressed, the specimens exhibited significant improvement in strength performance. At 14 days, an appreciable increase in compressive strength was recorded across all mix proportions, demonstrating the ongoing hydration of cement even when rubble sand was utilized. By 28 days, the results showed a clear distinction among the different mix ratios, with the 1:3 cement-to-sand proportion consistently achieving the highest compressive strength of approximately 24 MPa. This value suggests that mortars containing rubble sand at this ratio have potential for structural applications. On the other hand, mixtures with higher rubble content, such as the 1:6 and 1:8 ratios, showed limited performance, with compressive strength values below 10 MPa. These low strengths restrict their potential use to non-structural elements such as partition walls, plastering, or leveling layers.

The findings underline the potential role of crushed rubble sand in reducing reliance on natural sand while simultaneously addressing the problem of construction waste management. The study demonstrates that an appropriate mix design, particularly with higher cement proportions, can yield mortars that meet structural performance requirements. Nevertheless, further investigation is required to refine the material characteristics of rubble sand, particularly in terms of particle shape, surface texture, and bonding capacity, to enhance the resulting mortar's mechanical performance. Such efforts will improve the reliability of rubble-based mortars and contribute to advancing sustainable construction practices by promoting circular resource utilization in the building industry.

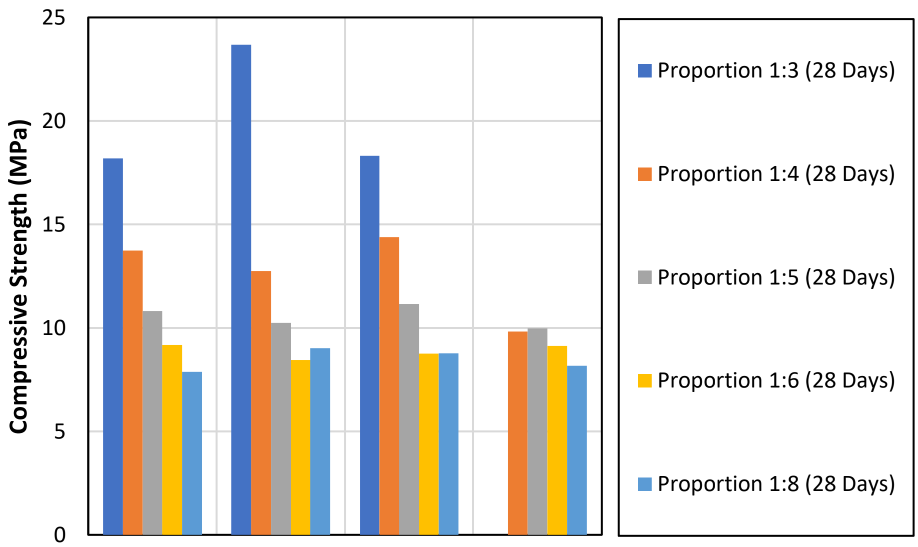

Figure 8. Compressive Strength Test Results with 28-Day Mortar Age

Building upon these previous studies, the present research further explores the utilization of recycled materials, particularly focusing on the fine fraction of demolition waste, which has often been considered less favorable due to its heterogeneous composition and relatively poor physical properties. According to (Wibowo, 2015) using recycled materials requires careful consideration of their origin to ensure that their use does not pose negative impacts, particularly those related to health and safety. The application of reclaimed materials in building construction can generally be classified into three categories: (1) re-used materials, which are employed in their original form and function without significant alteration; (2) refurbished materials, which undergo repair, modification, or adaptation to restore their performance or to serve a new function; and (3) reconstituted materials, which are processed or broken down into basic components to be re-used as raw materials in new construction products.

The study by Mardani et al. (2024) highlights the growing use of recycled aggregates derived from construction and demolition waste in the concrete industry. While the coarse fraction (5–20 mm) has been successfully recycled and reused, the fine fraction (0–5 mm) remains challenging due to its heterogeneous nature and poor physical properties. In this context, Mardani et al. investigated the feasibility of incorporating recycled mortar aggregate as a partial replacement for natural sand in pavement concrete, which inherently requires high resistance to weathering and abrasion.

The research involved three concrete strength categories prepared with different water-to-binder (w/b) ratios of 0.4, 0.5, and 0.6. The replacement levels of natural sand with recycled mortar aggregate ranged from 0% to 60% by volume, with incremental steps of 20%. The experimental results revealed that the adverse effects of recycled mortar aggregate on concrete durability are highly dependent on the strength category of the mix. Consequently, determining an appropriate maximum replacement level is essential to ensure that the reduction in performance remains within acceptable limits.

CONCLUSION

This study demonstrates the potential of recycled rubble sand from demolished walls as an alternative fine aggregate in mortar production. Material characterization confirmed a well-graded distribution, stable density values (SSD 2.48 g/cm³, bulk 2.35 g/cm³, apparent 2.71 g/cm³), and moderate water absorption (5.62%), although slight organic contamination was detected. Compressive strength tests revealed that a 1:3 cement-to-sand ratio achieved approximately 24 MPa at 28 days, indicating suitability for limited structural applications. However, higher substitution levels of rubble sand reduced strength, restricting its use to non-structural purposes.

Beyond the technical results, the findings provide important implications for post-earthquake housing reconstruction. Using recycled aggregates from demolition debris can help reduce waste, lower reconstruction costs, and accelerate rebuilding while promoting sustainable construction practices. To maximize these benefits, policymakers are encouraged to incorporate recycled construction and demolition materials into housing reconstruction programs and national building regulations. Such integration would support environmental sustainability, strengthen disaster recovery strategies, and enhance community resilience in disaster-prone regions.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the “Direktorat Jenderal Riset dan Pengembangan, Kementerian Pendidikan Tinggi, Sains, dan Teknologi Republik Indonesia (Program Penelitian Dosen Pemula BIMA Tahun 2025)”, for the financial support of this research through the Research Contract No. 1483ed/IT9.2.1/PT.01.03/2025, Fiscal Year 2025.

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