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CONTENT

Utilization of Recycled Brick and Concrete Aggregates in Cementitious Mortars: Physical and Mechanical Performance

Ahmet Ferdi ŞENOL[1*]

Cenk KARAKURT[2]

1- Lecturer.; Bilecik Şeyh Edebali Üniversitesi Mühendislik Fakültesi İnşaat Mühendisliği Bölümü. ahmetferdi.senol@bilecik.edu.tr ORCID No: 0000-0002-6663-3340

2- Prof. Dr.; Bilecik Şeyh Edebali Üniversitesi Mühendislik Fakültesi İnşaat Mühendisliği Bölümü. cenk.karakurt@bilecik.edu.tr ORCID No: 0000-0002-4204-5341

* Corresponding author,e-posta / e-mail:ahmetferdi.senol@bilecik.edu.tr

ABSTRACT

The sustainable utilization of construction and demolition waste is increasingly vital for reducing natural resource consumption and mitigating environmental impacts. The use of recycled brick aggregate (TA) and recycled concrete aggregate (BA) plays a crucial role in determining the performance and durability of cementitious mortars. This study investigates the effects of replacing river sand with TA or BA as fine aggregates in cementitious mortars, focusing on both fresh and hardened properties. A total of nine mortar series were prepared, and their performance was assessed through tests on workability, flexural strength, compressive strength, apparent porosity, and water absorption. The results revealed that a higher proportion of recycled aggregates led to a decrease in workability. Regarding 28-day flexural strength, the lowest strength reduction was observed in TA25 (7.4%) and BA25 (13.8%), whereas for compressive strength, TA25 (16.8%) and BA50 (3.6%) exhibited the least reduction. These findings quantitatively highlight the impact of recycled fine aggregates on mortar performance. While TA demonstrated acceptable mechanical properties when incorporated at up to 25%, BA exhibited a more significant enhancement in strength development when used up to 50%.

Keywords – Recycled aggregate, Brick aggregate, Concrete aggregate, Mortar, Mechanical properties

INTRODUCTION

In Türkiye, selective demolition processes are implemented in the construction industry to reduce environmental impacts and contribute to the economy. During this process, recoverable materials and hazardous substances such as asbestos are separated. Initially, roof coverings (tiles, coatings, etc.) are removed, followed by the segregation of reinforcement steel and recyclable materials (brick, concrete, etc.). Recyclable waste is sent to recycling facilities, while non-recyclable materials are directed to appropriate disposal sites (Akbaş and Çalışkan, 2024). Approximately 50% of the demolished buildings in construction demolition sites consist of fired clay-based bricks (red clay brick and hollow brick) and roof tiles, which are commonly used in partition walls and roof coverings. Various studies have confirmed that these wastes account for nearly half of the total demolition waste (Şenol and Karakurt, 2024).

In recent years, the utilization of construction and demolition waste has become a significant topic in renewable resource research. Although construction demolition waste accounts for 30–40% of municipal waste, the recycling process has been progressing slowly. The landfilling of waste aggregates leads to land loss and environmental pollution. Existing studies have primarily focused on recycled coarse aggregates, while research on recycled fine aggregates remains limited (Chen et al., 2024).

Aggregates serve as a primary constituent of concrete, with their physical and chemical characteristics exhibiting natural variability. The properties and strength of aggregates play a crucial role in shaping the overall performance of concrete. To ensure quality concrete production, it is vital to assess parameters such as particle size distribution, specific gravity, water absorption capacity, and resistance to abrasion. Natural aggregates constitute 70–80% of the concrete volume, and their consumption has been increasing rapidly due to the rise in concrete production. Natural river sand, which requires minimal processing and offers high quality, is commonly preferred as a fine aggregate. However, unregulated sand mining leads to ecological issues such as riverbank erosion, delta subsidence, loss of biodiversity, and depletion of water resources (Şenol and Çalışkan, 2024). Recycled aggregates generally exhibit higher water absorption and lower strength compared to natural aggregates due to their high porosity. This characteristic can limit cement hydration, thereby weakening the structure. Moreover, the existence of a dual interfacial transition zone (ITZ) within recycled concrete aggregate (RCA) contributes to a more intricate microstructure, often resulting in reduced performance relative to concrete made with natural aggregates (Gu et al., 2024). Hybrid aggregates containing recycled concrete (BA) and brick aggregates (TA) constitute approximately 60% of recycled aggregates. Therefore, coarse aggregates obtained from construction waste are often blended as recycled brick-concrete aggregates. However, TA exhibits higher porosity and lower mechanical properties compared to BA (Yuan et al., 2023).

A review of the existing literature suggests that as the quality of recycled aggregates improves, the strength loss in recycled aggregate concrete decreases. In this context, numerous researchers have investigated methods to enhance the compressive strength and durability properties of concrete produced with recycled aggregates. Dang et al. (2022) examined the effects of recycled fine aggregates derived from clay bricks on the mechanical and microstructural properties of concrete. In their study, recycled fine aggregates were used to replace natural fine aggregates at 25%, 50%, 75%, and 100% replacement levels, and concrete mixtures were prepared with varying additional water contents. The findings revealed that although the porous structure of recycled fine aggregates increased the total void volume, the pore sizes were reduced due to a more compact microstructure. Mechanical tests indicated that recycled fine aggregate concretes with no additional water or partial additional water (adjusted to 75% of the saturated surface dry condition) exhibited enhanced compressive and tensile strength. Nonetheless, studies have indicated that the elastic modulus of fully water-saturated recycled fine aggregate concretes experiences a negative impact. Sobuz et al. (2024) examined how variations in size and concentration of recycled concrete aggregates (RCA) influence the fresh and mechanical properties of high-strength concrete. In their study, recycled concrete aggregates of 5–12 mm and 12–20 mm were used to replace coarse natural aggregates at 0%, 15%, 30%, and 45% replacement levels, and different concrete mixtures were prepared. Fresh concrete tests included slump, Kelly ball, compaction factor, K-slump, and fresh density tests. The mechanical assessments included compressive strength, splitting tensile strength, and stress-strain analysis. Findings revealed that a higher proportion of recycled concrete aggregate negatively impacted both the fresh and hardened properties of concrete. However, concrete containing 5–12 mm RCA exhibited higher compressive and splitting tensile strength than those incorporating 12–20 mm RCA. Additionally, it was found that smaller-sized RCA resulted in lower embedded carbon emissions, offering a more sustainable solution. Singh et al. (2022) conducted a comparative evaluation of the effects of recycled fine aggregates (RFA) and recycled coarse aggregates (RCA), derived from concrete demolition waste, on the performance of concrete. In this research, concrete samples were produced by substituting natural fine aggregates with recycled fine aggregates at replacement levels of 30%, 60%, and 100%, while natural coarse aggregates were entirely replaced with 100% recycled coarse aggregates. The experimental results indicated that the fresh and mechanical properties of concrete incorporating recycled aggregates were generally lower compared to those containing natural aggregates. However, after 90 days of curing, a notable improvement in compressive strength was observed in concrete incorporating 30% recycled fine aggregates. In terms of density and water absorption, the study found that density was a more influential factor than water absorption capacity for recycled concrete aggregates. Notably, concrete produced with 30% recycled fine aggregates and natural coarse aggregates exhibited superior mechanical strength, making it a more advantageous alternative.

This study aims to explore the feasibility of utilizing recycled brick aggregate (TA) and recycled concrete aggregate (BA) as substitutes for river sand in cement-based mortars. To achieve this, nine distinct mortar series were formulated, incorporating TA and BA separately at volumetric replacement levels of 0%, 25%, 50%, 75%, and 100%. Following production, the flow table test was performed on the prepared mortar mixes, and their physical and mechanical properties were assessed after 7 and 28 days of standard curing.

MATERIALS and METHODS

Materials

In the production of the mortar series, CEM I 42.5 R Portland cement (specific gravity: 3.09) and river sand aggregate with a particle size range of 0–4 mm, sourced from local suppliers, were used. The recycled brick aggregates (TA) used in this study were obtained by crushing red clay bricks and hollow bricks from demolished buildings in Bilecik, Turkey, using a laboratory-scale jaw crusher. The crushed brick and concrete aggregates were initially subjected to oven drying at 105°C for 24 hours until achieving a stable weight. The brick aggregate mixture was prepared by replacing 50% hollow bricks and 50% red clay bricks. Additionally, recycled concrete aggregates (BA) were produced from demolished C25-C35 grade concrete using a similar crushing and screening process (Figure 1). These aggregates were sieved to 0–4 mm and sized according to the granulometry of river sand (Figure 2) for use as fine recycled concrete aggregates in mortar production. The specific gravity of river sand was determined as 2.6, its water absorption was 1.05% by weight, the fineness modulus was 2.55, and the maximum particle size was 4 mm. The chemical composition of the cement used in the mixtures is presented in Table 1.

Figure 1: Preparation of recycled brick aggregate and recycled concrete aggregate.

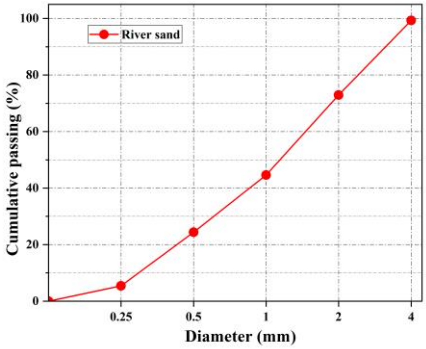

Figure 2: Grain size distribution curve of river sand.

Table 1: Cement's chemical characteristics.

Oxide Components, %	CEM I 42.5R
SiO_2	18.7
Al_2O_3	4.6
Fe_2O_3	3.4
CaO	63.7
MgO	1.3
SO_3	2.7
K_2O	0.7
Loss on Ignition (LOI)	3.9

Method

Nine distinct mortar mixtures were formulated in compliance with the TS EN 196-1 standard. Recycled brick aggregate (TA) and recycled concrete aggregate (BA) were used to replace river sand at volumetric replacement levels of 0% (C), 25%, 50%, 75%, and 100%. Across all mix series, the aggregate-to-binder ratio was maintained at 3, while the water-to-binder ratio was consistently set at 0.5. The target flow spread of the mortars was maintained within the range of 10–20 cm. The specific gravities of the brick aggregate (TA) and concrete aggregate (BA) were 2.63 and 2.30, respectively, while their water absorption rates by weight were 20.5% and 3.5%, respectively. These findings indicate that recycled brick aggregate and recycled concrete aggregate exhibit higher water absorption capacities compared to river sand. To ensure saturated surface dry (SSD) conditions, the required amount of additional water was incorporated into the mix to compensate for the water absorption of recycled brick and concrete aggregates.

The mortar series were designated as C, TA25, TA50, TA75, TA100, BA25, BA50, BA75, and BA100. In the series codes, the letters "TA" and "BA" represent brick aggregate and concrete aggregate, respectively, while the numbers indicate the percentage of aggregate replacing river sand by volume. For instance, the TA25 series refers to mortars containing 25% brick aggregate. The material compositions and quantities for each mortar series are presented in Table 2.

Table 2: Mix compositions of the mortar series.

Series	Cement (g)	TA (g)	BA (g)	Sand (g)	Water (g)	Additional Water (g)
C	450	-	-	1350	225	-
TA25	450	342	-	1012	225	70
TA50	450	684	-	675	225	140
TA75	450	1026	-	337	225	210
TA100	450	1368	-	-	225	280
BA25	450	-	298	1012	225	10
BA50	450	-	596	675	225	20
BA75	450	-	894	337	225	30
BA100	450	-	1192	-	225	40

During mortar preparation, cement and tap water were initially blended in a mortar mixer. Subsequently, the aggregates were incorporated, and the mixing process was continued. The flow table method, as specified in TS EN 1015-3/A2, was employed to assess the workability of the fresh mortars. The prepared mixtures were then poured into 40×40×160 mm prismatic molds in two layers, with each layer compacted using a vibrating table. After remaining in the molds for 24 hours, the specimens were demolded and subjected to curing in lime-saturated water at 20 ± 2°C for 7 and 28 days under laboratory conditions.

$$P\,(\%) = \frac{(w_1 - w_0)}{(w_1 - w_2)} \times 100 \tag{1}$$

$$WA\,(\%) = \frac{(w_1 - w_0)}{w_0} \times 100 \tag{2}$$

In the equation; w_0: represents the oven-dry weight of the specimen, w_1: represents the saturated surface-dry (SSD) weight of the specimen in air, w_2: represents the weight of the specimen in water.

Flexural and compressive strength tests were conducted on the mortar series in compliance with TS EN 1015-11 (Figure 3). All tests were performed using six specimens per series, and the obtained results were evaluated using the arithmetic mean method.

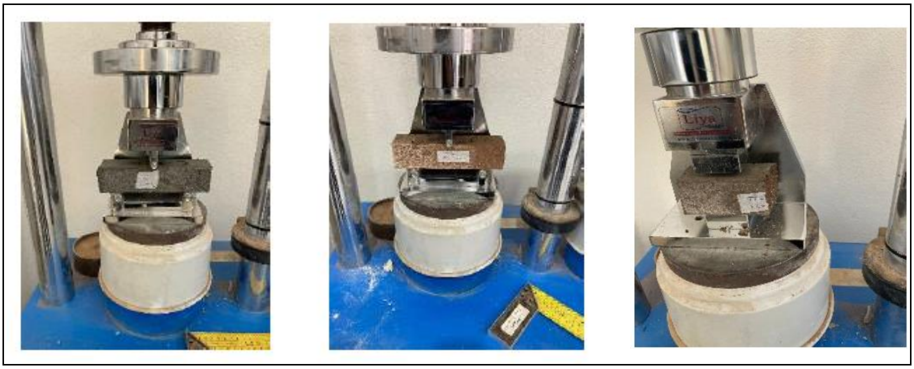

Figure 3: Flexural and compressive strength tests.

RESULTS AND DISCUSSION

Fresh Mortar Test Results

The workability properties of the mortar series in the fresh state were determined using the flow table test. The variations in the measured flow diameters are presented in Figure 4.

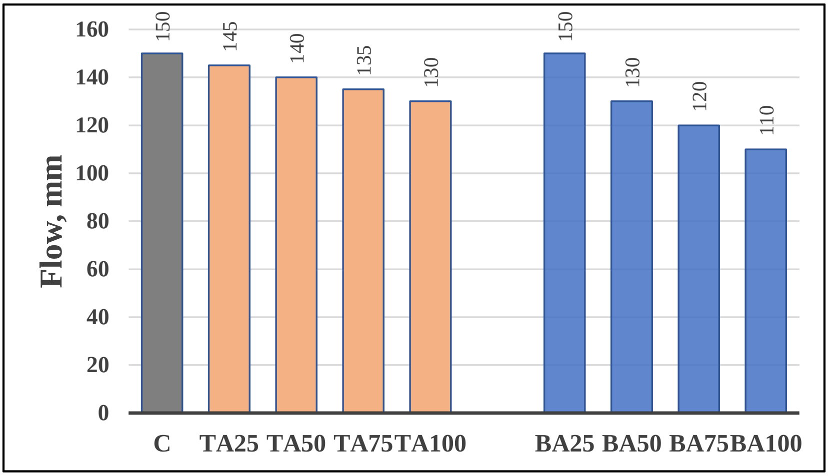

Figure 4: Variation in flow diameters of the mortar series.

Based on the flow diameter measurements presented in Figure 4, it was observed that as the recycled aggregate content (TA and BA) increased, the flow diameters of the mortar series decreased. Compared to the C series, the flow diameters of the TA series decreased by 3.3%, 6.7%, 10%, and 13.3% for TA25, TA50, TA75, and TA100, respectively. Similarly, for the BA series, the reductions were 0%, 13.3%, 20%, and 26.7%, respectively.

In both TA and BA series, workability decreased as the aggregate replacement ratio increased. This phenomenon can be attributed to the rougher surface texture and irregular angular shape of TA and BA compared to river sand, which increases friction between particles and raises water absorption during flow.

Notably, in the BA series, the flow diameters decreased more significantly from 50% replacement onward compared to the TA series. This can be explained by the higher initial porosity of brick aggregates (TA) compared to concrete aggregates (BA), leading to higher water absorption at the beginning of mixing. However, during the mixing process, brick aggregates tend to release the absorbed water back into the mixture, resulting in higher workability in the TA series compared to the BA series.

Flexural and Compressive Strength Test Results

Figures 5 and 6 illustrate the changes in flexural and compressive strength of the mortar series following 7 and 28 days of curing. It was observed that as the curing duration increased, both flexural and compressive strengths improved.

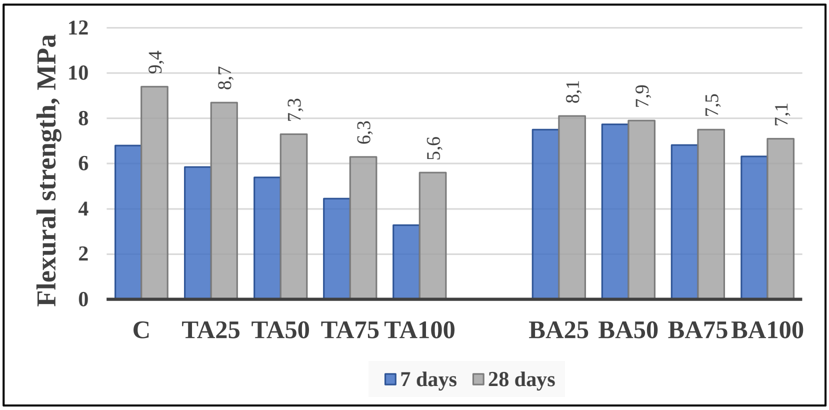

Figure 5: Flexural strengths of the mortar series at 7 and 28 days.

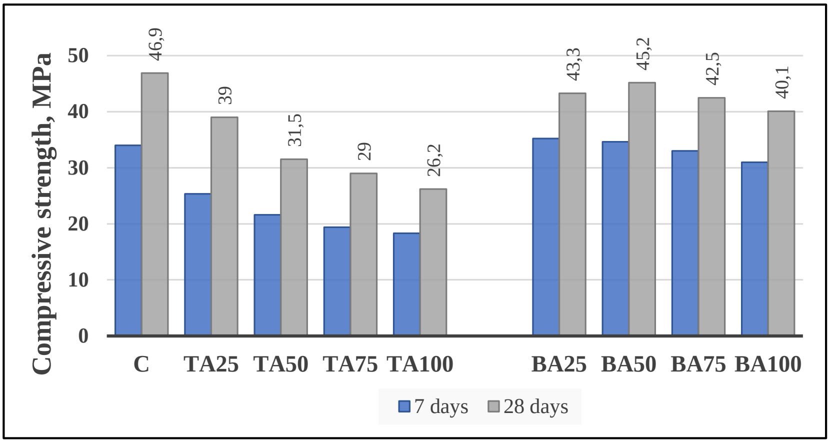

Figure 6: Compressive strengths of the mortar series at 7 and 28 days.

The 7-day flexural strengths of the TA series ranged between 3.3–5.9 MPa, whereas those of the BA series were within the 6.3–7.7 MPa range. As seen in Figure 5, the 7-day flexural strengths of the TA series continuously decreased with TA replacement compared to the C series. However, in the BA series, BA25 and BA50 exhibited an increase of 10.3% and 13.7%, respectively, while BA75 showed a marginal increase of 0.3%. In contrast, BA100 resulted in a 7.1% decrease. It is suggested that the filling and nucleation effects of BA can contribute to enhancing the flexural strength when an optimal BA replacement ratio is used (Wu et al., 2025). After 28 days of curing, the flexural strengths of the TA series ranged between 5.6–8.7 MPa, while those of the BA series varied between 7.1–8.1 MPa. As shown in Figure 5, the flexural strengths of both the TA and BA series decreased at all replacement levels compared to the C series. The lowest strength loss was observed in TA25 (7.4%) and BA25 (13.8%).

The 7-day compressive strengths of the TA series ranged between 18.3–25.3 MPa, while those of the BA series varied between 31–35.2 MPa. As shown in Figure 6, the 7-day compressive strengths of both TA and BA series continuously decreased with aggregate replacement compared to the C series. After 28 days of curing, the compressive strengths of the TA series ranged between 26.2–39 MPa, while those of the BA series varied between 40.1–45.2 MPa. Accordingly, the compressive strengths of both TA and BA series decreased at each replacement level compared to the C series. However, the lowest strength loss was observed in TA25 (16.8%) for the TA series and BA50 (3.6%) for the BA series. Previous studies indicate that the effect of recycled concrete aggregate (BA) on compressive strength varies depending on the replacement level. The increased surface roughness of BA may contribute to the formation of a stronger interfacial transition zone (ITZ) with the new mortar matrix, leading to a slight improvement in early-age compressive strength. However, the porosity and microcracks in BA increase its water absorption, which can elevate the water-to-cement ratio in the aggregate-mortar ITZ, weakening the bond. When the BA content exceeds 50%, these negative effects become dominant, causing a decrease in compressive strength (Xuyong et al., 2025). A study by Wang et al. (2022) also reported that recycled coarse aggregates (water absorption: 5%) obtained from construction demolition waste, when used at 50% replacement, led to an increase in compressive strength due to ITZ improvement, internal curing, and a well-balanced aggregate combination. However, when BA replacement exceeded 50%, the increased porosity and microcracks resulted in a reduction in strength. The findings of Wang et al. (2022) are consistent with the results obtained in the present study. Similarly, Wu et al. (2025) found that BA replacement up to 40% improved mortar compressive strength, whereas further replacement levels led to a gradual decline in strength. The observed strength enhancement was attributed to the filling and nucleation effects of BA, as well as the promotion of cement hydration by SiO_2 and $Ca(OH)_2$ in BA, which facilitated the formation of additional hydration products, filling the pores of the mortar matrix.

Figure 7 displays the correlation between the 7-day and 28-day flexural and compressive strengths of the TA series, whereas Figure 8 presents the correlation results for the BA series. Accordingly, a strong and positive correlation ($R^2 > 0.9$) was observed among the 28-day strength results of the TA series and among the 7-day strength results of the BA series.

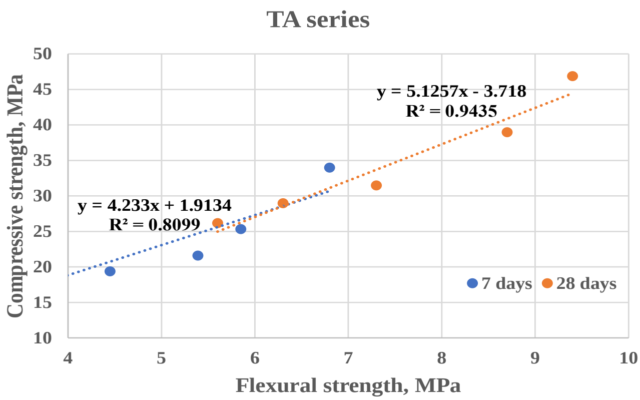

Figure 7: Relationship between the 7-day and 28-day flexural and compressive strengths of the TA series.

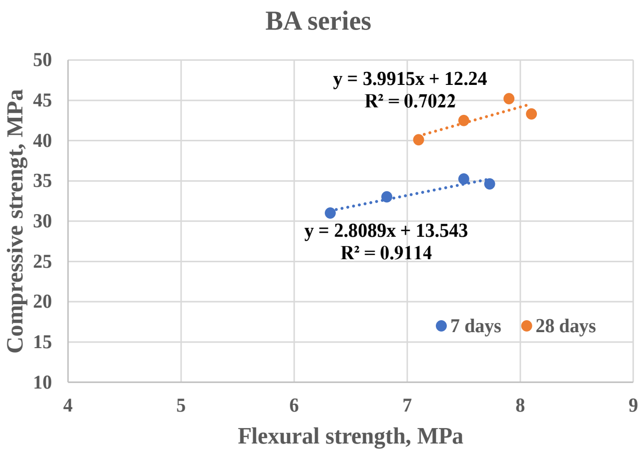

Figure 8: Relationship between the 7-day and 28-day flexural and compressive strengths of the BA series.

Apparent Porosity and Water Absorption Test Results

The variations in apparent porosity and water absorption by weight of the mortar series after 28 days of curing are presented in Figures 9 and 10, respectively.

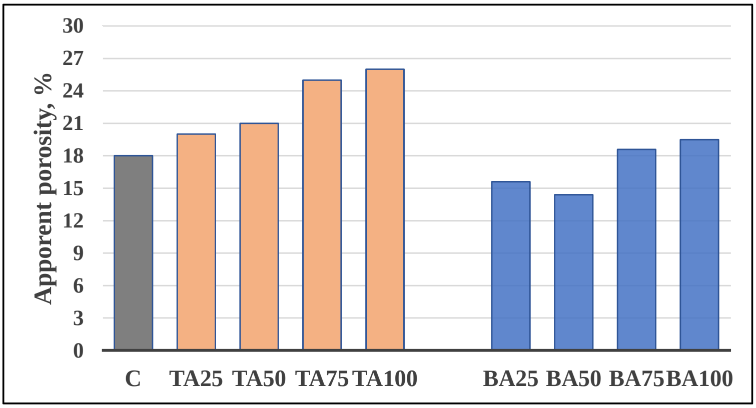

Figure 9: Apparent porosity results of the mortar series after 28 days of curing.

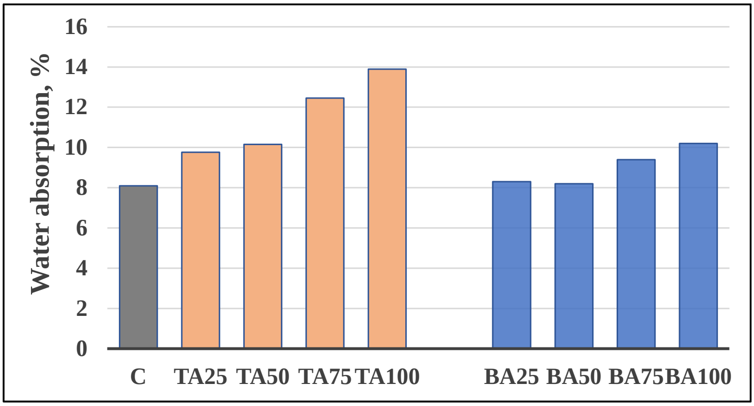

Figure 10: Water absorption results of the mortar series after 28 days of curing.

The apparent porosity of the C series was determined as 18%, while its water absorption value was 8.1%. The 28-day apparent porosity values ranged between 20–26% in the TA series and 14.4–19.5% in the BA series. It was observed that apparent porosity and water absorption increased with the increase in TA content. In the BA series, apparent porosity values decreased up to BA50 compared to the C series, but increased at BA75 and BA100. The water absorption values ranged from 9.8–13.9% in the TA series and 8.2–10.2% in the BA series. Similar to the apparent porosity trends, the water absorption values of the TA series increased with the increase in TA content. In the BA series, BA25 (2.5% increase) and BA50 (1.2% increase) exhibited water absorption values closest to the C series, whereas BA75 and BA100 showed increases of 16% and 25.9%, respectively. The increase in apparent porosity in the mortar series is associated with higher water absorption, which can lead to a decline in durability performance (Şenol and Çalışkan, 2024).

CONCLUSION

The findings obtained from the experimental study are summarized as follows;

- Workability decreased with increasing TA and BA replacement levels in mortars containing recycled aggregates. Compared to the C series, the flow diameter decreased by 3.3% to 13.3% in the TA series and up to 26.7% in the BA series. This reduction was attributed to the rough texture and high water absorption capacity of the aggregates.
- The higher water absorption capacity of recycled TA and BA compared to natural aggregates suggests that these aggregates should be pre-saturated to a water-saturated condition before being used in cementitious mortar mixtures. Alternatively, incorporating additional water or superplasticizers into the mix could be a suitable approach to enhance workability.
- The 28-day flexural strengths of the TA and BA series decreased at all replacement levels compared to the C series. The lowest strength loss was observed in TA25 (7.4%) and BA25 (13.8%).
- Compressive strength decreased in all series compared to the C series. However, the lowest strength loss was recorded in TA25 (16.8%) for the TA series and BA50 (3.6%) for the BA series. While BA replacement up to 50% maintained compressive strength relatively well, higher replacement levels led to strength loss due to increased porosity and microcracks.
- The TA series exhibited a more noticeable rise in apparent porosity and water absorption, whereas in the BA series, these properties remained relatively stable up to BA50 but showed a significant increase at BA75 and BA100. The higher porosity and water absorption in the mortar series may negatively impact durability performance, emphasizing the need to optimize aggregate replacement levels.

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Review of Strengthening Techniques for Masonry Structures: Advances and Applications

Ali Ekber SEVER[1]

Elifnur ŞAKALAK[2]

Pınar Usta EVCİ[3]

1- Res. Asst. ; Isparta University of Applied Sciences, Faculty of Technology, Department of Civil Engineering alisever@isparta.edu.tr ORCID No: 0000-0001-5314-5287
2- Res. Asst. ; Isparta University of Applied Sciences, Faculty of Technology, Department of Civil Engineering elifnursakalak@isparta.edu.tr ORCID No: 0000-0002-8624-5337
3- Ass. Prof.. ; Isparta University of Applied Sciences, Faculty of Technology, Department of Civil Engineering pinarusta@isparta.edu.tr ORCID No: 0000-0001-9809-3855

ABSTRACT

Masonry structures are an integral part of global architectural heritage and modern construction due to their durability, thermal insulation, and cost-effectiveness. However, they are highly susceptible to seismic forces, requiring advanced strengthening techniques to enhance their resilience and safety. This paper reviews the state-of-the-art methods for reinforcing masonry buildings, focusing on innovative approaches such as fiber-reinforced polymers (FRPs), fiber-reinforced cementitious matrices (FRCMs), and reinforced panel systems. The paper highlights their effectiveness, limitations, and practical applications, providing valuable insights into optimizing masonry structures for both preservation and contemporary needs. The findings underscore the importance of integrating traditional and modern techniques to ensure the seismic resilience and longevity of masonry buildings.

Keywords – Masonry Structures, Strengthening Techniques, Fiber-Reinforced Polymers (FRPs), Fiber-Reinforced Cementitious Matrices (FRCMs), Reinforced Panel Systems, Seismic Resilience, Structural Retrofitting

INTRODUCTION

Masonry structures are widely used by more than one-third of the global population due to their local availability, recyclability, cost-effective sustainable construction, as well as favorable thermal performance and acoustic insulation properties compared to reinforced concrete and steel structures. However, recent seismic events have highlighted their structural vulnerability, often resulting in brittle and sudden failures. Notable examples include the 2003 Bam earthquake in Iran, the 2009 L'Aquila earthquake in Italy , the 2019 Durres earthquake in Albania, 2020 Samos earthquake, and 2022 Maraş earthquakes in Turkey (Latifi et al., 2023).

Masonry structures constitute a significant portion of the building stock in our country, with their load-bearing system consisting solely of walls. Due to their almost negligible deformation capacity, they have low energy dissipation potential and are highly prone to sudden and brittle failures during earthquakes. Furthermore, these structures are susceptible to significant negligence and errors during the construction phase. As a result, masonry structures are among the most damaged during earthquakes and are often associated with considerable loss of life. A large proportion of these structures are located in earthquake-prone regions, making the implementation of permanent, practical, and economical strengthening solutions critically important. The diversity of masonry structures depends on several factors, such as the climatic conditions of the region where they are built, the availability of local materials, cultural characteristics, and the income and education level of the building owner. These structures are categorized into four main groups: brick, concrete block, adobe, and natural stone. During construction, these materials are stacked using a binding material to form walls. The walls transfer vertical loads to the ground, while the floors can be made of reinforced concrete or wood. Roofs, on the other hand, may consist of materials such as earth-covered roofs, clay tiles, or galvanized sheets (Korkmaz, 2007; Yalnız 2020).

Masonry structures, spanning from historical landmarks to modern constructions, are vital components of architectural heritage and civil infrastructure. Despite their historical significance and aesthetic value, masonry structures are susceptible to damage due to seismic activity, environmental factors, and material degradation over time. Effective strengthening methods are essential to ensure their longevity and resilience.

This review discusses the state-of-the-art techniques for strengthening masonry structures, providing a comparative analysis of their effectiveness based on recent research. The focus is on innovative materials such as fiber-reinforced polymers (FRPs), fiber-reinforced cementitious matrices (FRCMs), and traditional methods such as steel reinforcement. Additionally, the role of advanced modeling techniques in optimizing these interventions is highlighted.

Masonry buildings are generally constructed using materials such as stone, brick, and mortar, which exhibit high compressive strength but limited tensile strength (Lourenço, 1996). These structural limitations make them vulnerable to horizontal forces, such as those induced by earthquakes. Therefore, strengthening strategies must address the unique material properties of masonry to effectively mitigate seismic risks.

Masonry structures have been widely preferred throughout history due to their ability to be built with local materials and their low cost. However, these structures are vulnerable to earthquakes, strong winds, and other external factors. Therefore, strengthening masonry structures is critical to increasing their durability and safety.

To evaluate the importance given to masonry structures, a scientific analysis was conducted using the Scopus database to examine academic studies published worldwide over the past five years. A search in the Scopus database using the keywords "Masonry structures" and "strengthening" together identified a total of 3,012 articles. The analysis was limited to publications from the years 2020-2025 and focused exclusively on the field of engineering.

The results are presented in Figures 1 and 2. Figure 1 illustrates the number of publications by year, while Figure 2 highlights the authors with the highest number of publications in this field. These findings reveal the increasing global interest in strengthening masonry structures and provide detailed insights into the scientific contributions in this area.

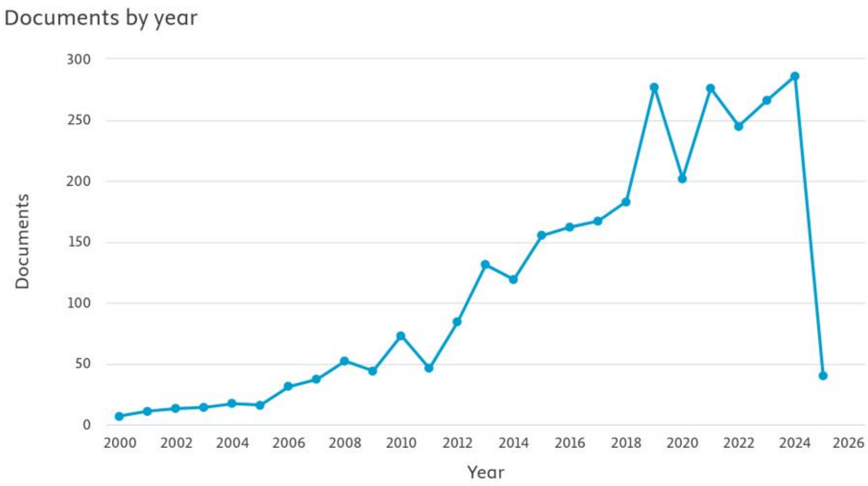

Figure 1: The Number of Documents by Year From Scopus

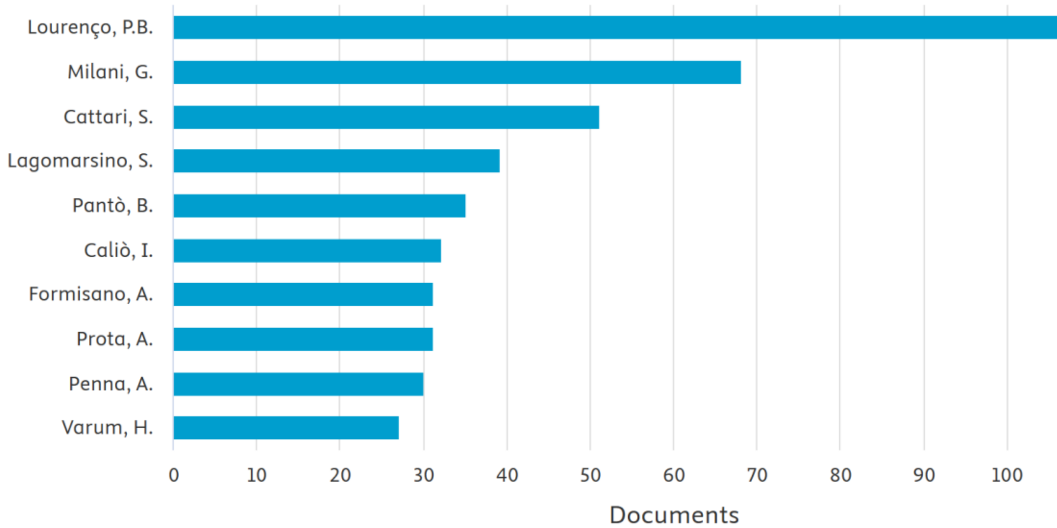

Figure 2: Top 10 Authors with the Most Publications by Number of Documents From Scopus

LITERATURE REVIEW

The strengthening of masonry structures has been extensively studied, leading to the development of various innovative techniques. Fiber-reinforced polymers (FRPs) have emerged as a highly effective method due to their lightweight nature and high tensile strength.

Altunişik (2011) examined the effectiveness of FRP materials in improving the dynamic response of masonry minarets, revealing significant structural enhancements. Similarly, Alecci et al. (2016) conducted experimental studies on masonry arches reinforced with PBO-FRCM composites, demonstrating their effectiveness in increasing load-bearing capacity. In terms of environmental adaptability, Bayraktar and Hökelekli (2021) analyzed the nonlinear effects of soil flexibility on seismic damage mechanisms in masonry arch bridges, emphasizing the critical role of soil-structure interaction in the design process. Expanding on this research, Güllü and Jaf (2016) conducted a full-scale 3D nonlinear time history analysis of a historical masonry arch bridge, providing detailed insights into dynamic soil-structure interactions.

Vicente et al. (2010) developed three-dimensional finite element models of four traditional masonry buildings in Coimbra, Portugal, to assess their structural vulnerability and analyze observed damage patterns. Giamund et al. (2014) compared the continuous (FEM) and discrete (DEM) element methods to evaluate the behavior of low-strength masonry structures, contributing to the selection of the most efficient and cost-effective modeling strategy. Ural et al. (2016) assessed the performance of different tie rod configurations in arch specimens through both experimental and numerical methods, identifying the most suitable reinforcement model for historical structures.

Carozzi et al. (2018) carried out an in-situ experimental study on a historic building in Italy, reinforcing its vaults and arches with FRP, TRM, and SRG composite materials. By applying vertical loads, they compared the structural performance in terms of load-bearing capacity, stiffness, and failure mechanisms. Zani et al. (2019) explored the seismic behavior of a 14th-century stone arch bridge using advanced computational techniques, highlighting the significance of soil-structure interaction, findings that align with Lourenço's (1996) foundational computational strategies for masonry analysis. Lourenço (2021) examined the analytical possibilities of historical structures through basic examples such as a wall and a wall arch subjected to out-of-plane loading, presenting case studies of varying complexity and offering general recommendations for modeling.

Wang et al. (2022) introduced ultra-high-performance concrete (UHPC) as a strengthening material for stone arch bridges, demonstrating its potential to enhance both structural durability and aesthetic preservation. Boem (2022) applied detailed-level numerical modeling to simulate TRM-reinforced masonry elements subjected to diagonal compression and bending tests, investigating common failure mechanisms through nonlinear static analyses. Rotunno et al. (2022) developed a micro-mechanical finite element model to replicate the behavior of masonry walls strengthened with CFRP sheets under out-of-plane loading.

Bayraktar et al. (2023) provided a comprehensive review of theoretical and experimental studies on the response and strengthening of masonry domes under static and dynamic loads. They analyzed crack formations and failure mechanisms and evaluated both traditional and modern reinforcement techniques in accordance with conservation principles. Tanrıverdi (2023) tested six different masonry vault specimens under axial compression, including one reference sample, one connecting rod, and four CFRP-reinforced designs, followed by numerical analyses in the LUSAS software to compare with experimental results.

Uysal and Usta (2024) evaluated the seismic performance of a registered masonry building in Isparta. Their study involved material characterization through experimental tests based on Turkish Standards, numerical modeling using Sap2000, and the application of FRP reinforcement within the digital model. Finally, Salvallagio et al. (2024) performed an updated fragility analysis of Lisbon's pre-code masonry buildings using the Applied Element Method. After identifying structural vulnerabilities, they modeled and assessed two different scaffolding-based reinforcement strategies for buildings with insufficient seismic capacity.

ASSESSMENT OF MASONRY STRUCTURES

In masonry buildings, the structural system relies on load-bearing walls. These walls are constructed using elements such as bricks, stones, concrete blocks, or aerated concrete, commonly referred to as masonry units. The classification of masonry structures is determined based on the type of these units.

According to TBDY (2018), masonry buildings are categorized into four main types:

- **Unreinforced masonry structures**,
    - Stone masonry buildings
    - Adobe masonry buildings
    - Brick masonry buildings
- **Confined masonry structures**
- **Reinforced masonry structures**
- **Reinforced panel system structures**

Unreinforces Masonry Structure

Stone Masonry

These are structures (Figure 3) where the load-bearing walls are typically constructed using natural stones, with the horizontal and vertical joints between these masonry units filled with binding mortar. Natural stone masonry units offer advantages such as thermal and sound insulation, as well as fire resistance (TS EN 771-6, 2015). However, due to the heavy and brittle nature of the materials used, these buildings have limited ductility and exhibit low resistance to horizontal forces, such as those caused by earthquakes.


Figure 3: Stone Masonry Building (Atabey, 2025)

Adobe Masonry

Adobe is a construction material commonly used in rural areas, such as towns and villages. According to the Turkish Language Institution, adobe is defined as a primitive wall material made by mixing clay and straw, pouring it into molds, and allowing it to dry under the sun. The primary disadvantage of adobe is its low resistance to water. Furthermore, sudden temperature changes can cause material degradation due to salt crystallization. Another significant drawback of adobe is its low resistance to both vertical and horizontal loads, which limits its usability.

Although adobe buildings (Figure 4) can still be found in rural villages across the country, the use of adobe as a building material has been prohibited in the 2018 Turkish Building Earthquake Code, despite related provisions for adobe construction being included in the 1998 and 2007 Building Earthquake Codes (Özgünler and Gürdal, 2012; Resmi Gazete, 2018; Leblebiciler and Akıncı, 2021; Yavaş, 2021).

Figure 4: Adobe Masonry Building (Karakul, 2025)

Brick Masonry Structure

Brick masonry structures (Figure 5) are constructed using artificial building materials produced by mixing clay soil with water, sand, ground brick or tile powder, and similar materials to form a clay paste, shaping it according to its intended use, and firing it in kilns. Solid or perforated bricks are used in the walls of these structures. During wall construction, vertical continuity of the perforations is ensured, and the walls are built using binding beams and cement mortar. These structures exhibit brittle behavior compared to reinforced concrete buildings due to the mechanical properties of the materials used, which are not sufficiently suitable for resisting seismic forces. Since they lack adequate deformation capacity, horizontal tie beams are added at floor levels during construction, in addition to lintels over doors and windows. In cases of greater story height, intermediate horizontal tie beams, as well as vertical tie beams near door and window openings and wall edges, can be incorporated to provide behavior similar to the ductility offered by columns in reinforced concrete buildings. While these tie beams were traditionally made of wood, modern construction predominantly uses reinforced concrete applications, incorporating rebar within the wall thickness. Reinforced concrete vertical tie beams are integrated into the building by filling vertical gaps, with the surrounding brick walls serving as formwork. Studies on the seismic behavior and safety of masonry structures indicate that various measures must be taken to enhance their seismic resistance. In particular, the use of horizontal and vertical tie beams plays a significant role in improving the seismic performance of masonry structures (Bayülke, 2011; Koç, 2016; Korkmaz, 2017; Yalnız, 2020).

Figure 5: Brick Masonry Structure (ınsapedia, 2015)

Confined Masonry Structure

Confined masonry buildings (Figure 6) differ from unreinforced masonry structures by incorporating horizontal and vertical reinforced concrete tie beams. These tie beams are constructed after the load-bearing walls are built, using the walls as formwork, and are connected to each other and to the slabs as reinforced concrete structural elements. According to the Turkish Building Earthquake Code (TBDY, 2018), confined masonry buildings are classified as limited ductility structures. At first glance, these buildings may resemble reinforced concrete structures. However, a key distinction lies in the relatively small dimensions of the reinforced concrete sections, with horizontal tie beams often being so small that they appear to disappear within the masonry walls. Additionally, many ductility and capacity design principles required for reinforced concrete structures are not applied in these buildings, and the horizontal and vertical tie beams are not designed according to reinforced concrete calculations (Smyrou, 2017; TBEC, 2018; afad, 2025; Insapedia, 2025)

Figure 6: Confine Masonry structure (Smyrou, 2017)

Reinforced Masonry Structure

Reinforced masonry buildings (Figure 7) are a type of structure with high ductility, constructed by placing reinforcement in load-bearing walls in compliance with the relevant regulations (TBDY, 2018). The use of low-ductility materials in masonry buildings leads to sudden and brittle failures, which consequently results in low earthquake resistance. In reinforced masonry buildings, horizontal and vertical reinforcements are incorporated into masonry walls to enhance their ductility and improve their strength, making the structures more earthquake-resistant. Observations from past earthquakes have shown that confined and reinforced masonry buildings perform well under seismic loads, whereas unreinforced masonry buildings fail to achieve the same level of performance. Reinforced masonry buildings have higher ductility levels compared to confined and unreinforced masonry structures, exhibiting better performance under seismic loads. Additionally, the maximum building heights and number of stories permitted for these structures in earthquake codes are greater. Although not yet widely adopted, the number of such masonry buildings is expected to increase in the coming years with the introduction of the new earthquake regulations. (Genes et al., 2017).

Figure 7: Reinforced Masonry Structure (Atabey, 2025)

Reinforced Panel System Structures

Reinforced panel system buildings (Figure 8) are modern structures constructed using reinforced autoclaved aerated concrete (AAC) panels as load-bearing walls and other structural elements. In this system, reinforced AAC panels designed to resist both vertical and horizontal loads are utilized as walls, floors, and roof components. These panels offer advantages such as high thermal insulation, energy efficiency, fire safety, and earthquake resistance. Additionally, their lightweight nature helps reduce the overall weight of the structure, thereby decreasing seismic loads Reinforced panel system buildings also contribute to cost efficiency by reducing construction time. They are suitable for various types of structures, including residential buildings, schools, and tourism facilities, across different climates and geographic conditions. (Ytong, 2025)

Figure 8: Reinforced Panel System Structure

Behavior of Masonry Structures

Masonry structures are inherently vulnerable, particularly at the joints where masonry units are bonded to the mortar. These joints represent the weakest link in the structural system, often dictating the overall stability of the structure. A defining characteristic of masonry behavior is its pronounced non-linearity, especially at these interfaces. The mechanical response of masonry is significantly influenced by the interaction between the mortar and the masonry units, with failures at this interface occurring in two primary modes:

- Mode I (Tensile Failure) – This occurs when the tensile strength of the mortar-masonry interface is exceeded, leading to separation or cracking.
- Mode II (Shear Failure) – This takes place when the shear forces surpass the shear strength of the interface, resulting in sliding or delamination between the mortar and the masonry unit.

Due to these inherent weaknesses, masonry structures are highly susceptible to seismic forces. Even moderate earthquakes can cause significant structural distress, including extensive cracking, partial collapses, or complete structural failure. The unpredictable nature of seismic events further exacerbates this vulnerability, making unreinforced masonry (URM) buildings a major source of economic losses and posing a severe risk to human safety. The collapse of masonry structures during seismic events has historically led to considerable casualties and long-term socio-economic disruptions. Cattari et al. (2022); Kyriakides et. Al. (2023); Blagojević et al. (2023); Keshmiry et al. (2024)

Given these risks, seismic strengthening techniques play a vital role in enhancing the resilience of masonry structures. Retrofitting strategies such as Fiber-Reinforced Polymer (FRP) applications, Textile-Reinforced Mortar (TRM) reinforcements, or steel tie rod systems can significantly improve structural integrity, energy dissipation capacity, and overall seismic performance. Implementing these techniques is essential for preserving historical masonry structures and ensuring the safety of both occupants and surrounding environments.

Figure 9 illustrates the distribution of unreinforced masonry (URM) buildings across European countries and presents the total number of buildings in millions, highlighting the widespread presence of masonry structures and the pressing need for effective strengthening solutions

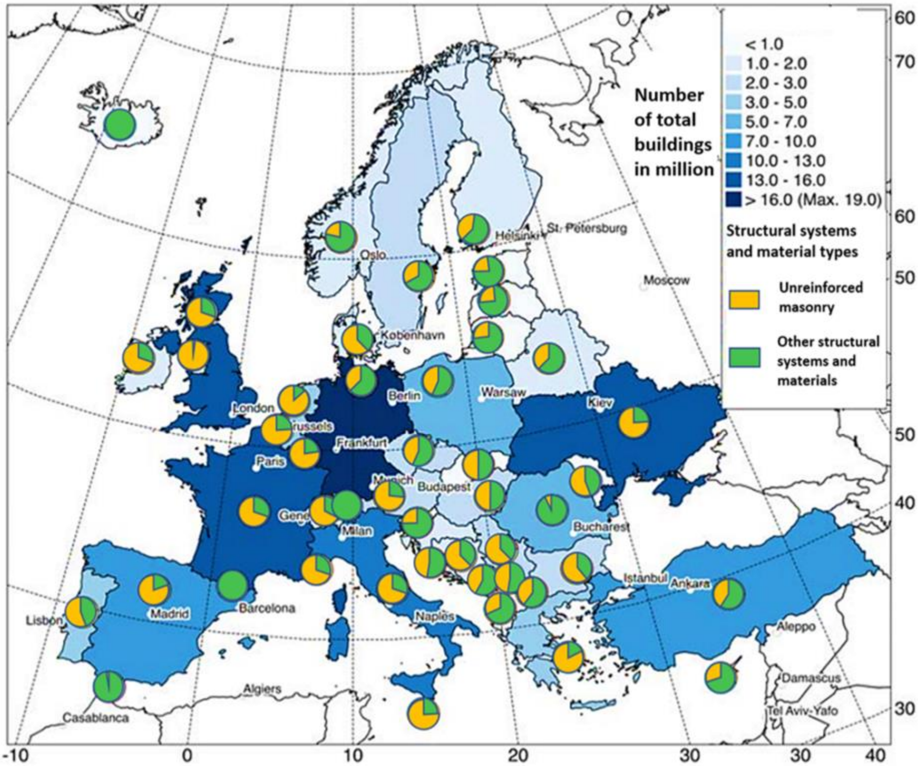

Figure 9: Unreinforced Masonry (URM) Buildings Across European Countries Shabani et al. (2021)

TRADIONAL STRENGTHENING METHODS

Steel Reinforcement

Steel has long been used to strengthen masonry structures (Figure 10) due to its high tensile strength and availability. Studies indicate that steel tension rods are particularly effective in controlling lateral displacements and enhancing load-bearing capacity (Tuğrulelçi, 2014). However, the susceptibility of steel to corrosion and its impact on the aesthetic value of historical structures remain significant concerns.

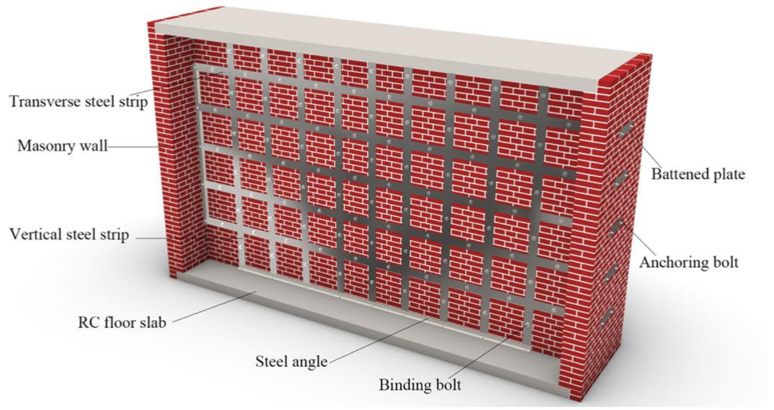

Figure 10: Schematic Diagram Of A Masonry Wall Strengthened By Steel Strips (Jing et al., 2021)

Grouting Techniques

Grouting is a traditional method involving the injection of mortar into voids or cracks in masonry structures (Figure 11). This technique enhances the bond between masonry units, improves shear resistance, and reduces water infiltration. While effective, grouting is labor-intensive and may not be suitable for large-scale applications.

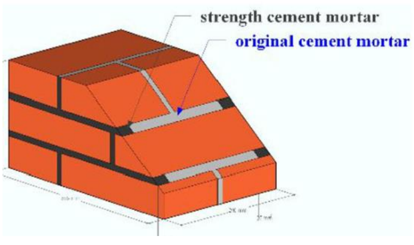

Figure 11: Strengthening Grouting Techniques on Masonry

INNOVATIVE STRENGTHENING TECHNIQUES

Fiber-Reinforced Polymers (FRPs)

FRPs, including carbon and glass fiber variants, have emerged as popular choices for masonry reinforcement due to their lightweight, high tensile strength, and corrosion resistance (Altunişik, 2011). Research has demonstrated that the application of FRP sheets (Figure 12) to the intrados of masonry arches significantly increases their load-bearing capacity (Alecci et al., 2016; Alecci et al., 2017).

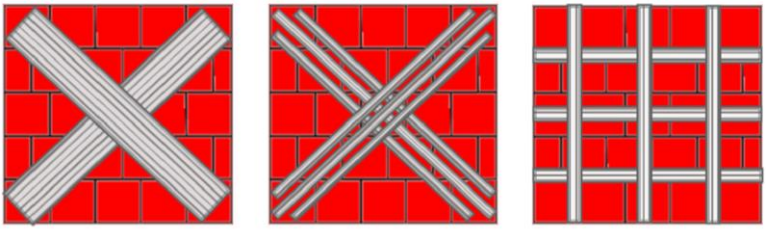

Figure 12: Strengthening layouts of FRP application over the masonry wall surface (Thomoglou et al., 2023)

However, the performance of FRPs is highly dependent on environmental factors such as temperature and humidity, which can adversely affect their adhesion properties (Garmendia et al., 2015). Future research should investigate the long-term durability of FRPs in varying climatic conditions and their compatibility with different masonry materials.

The primary categories of FRP include Glass, Aramid, and Carbon fiber-reinforced polymers (GFRP, AFRP, and CFRP). These materials, commonly utilized for structural strengthening or retrofitting, are available in various commercial forms such as laminates, meshes, tendons, and rods (Babatunde, 2016). A summary of the effectiveness, benefits, and drawbacks of these techniques is provided in Table 1.

Table 1: The Efficiency, Advantage, Disadvantage Of The FRP Techniques (Babatunde, 2016)

Technique	Efficiency (In-Plane)	Efficiency (Out-of-Plane)	Advantage	Disadvantage
Externally Bonded FRP System	Enhances lateral stiffness and deformation control.	Strengthens flexural capacity, ductility, and stability.	Boosts flexural and shear resistance. Enhances seismic performance. Easy to install and apply.	Prone to early debonding failures. Loses effectiveness at high temperatures. UV sensitivity. High upfront cost. Vulnerable to environmental factors.
Near Surface Mounted FRP Systems	Enhances out-of-plane	Increases lateral force resistance.	Improves post-cracking flexural	Susceptible to debonding due to epoxy failure or

	bending capacity.		strength and ductility. Quick application. Fire and UV protection.	substrate cracking.
Center Core Technique	Doubles unreinforced masonry resistance.	Increases lateral resistance.	Maintains original architectural aesthetics. No impact on building use.	Does not reduce usable space. Results in regions with different stiffness and strength properties.
Cement-Based Matrix Grid System	N/A	N/A	Improves load-bearing capacity. Polymer grids provide additional stiffness and strength.	Potential grid slippage or tensile rupture.
FRP Strip Strengthening Technique	Increases strength, ductility, and energy dissipation. Enhances lateral resistance up to four times the original capacity.	Reduces displacement.	Increases overall stability without adding significant weight.	N/A
Micro-Reinforcement of Masonry Joints	N/A	N/A	Enhances mortar flexibility and toughness. Improves compressive strength.	N/A
Macro-Reinforced Masonry Joint	N/A	N/A	Strengthens mortar in terms of flexibility, toughness, compression, and tension. Improves ductility and crack resistance.	N/A
Post-Tensioning	Improves in-plane lateral resistance.	Enhances lateral resistance.	Increases resistance to cracking and ultimate load capacity. No additional	High losses over time. Risk of corrosion in anchorage components.

		mass. No interference with building function.

Fiber-Reinforced Cementitious Matrices (FRCMs)

FRCMs have gained attention as an alternative to FRPs, particularly for historical masonry structures. Unlike FRPs, FRCMs are more compatible with the substrate and perform well in high-temperature environments (Wang et al., 2022). Reinforcement schemes of FRCM/TRM application on brick masonry wall are shown in Figure 13. Studies have shown that FRCMs can effectively enhance the ductility and deformation capacity of masonry walls (Bayraktar and Hökelekli, 2021). Further exploration of their mechanical properties and behavior under cyclic loading is needed to expand their application scope.

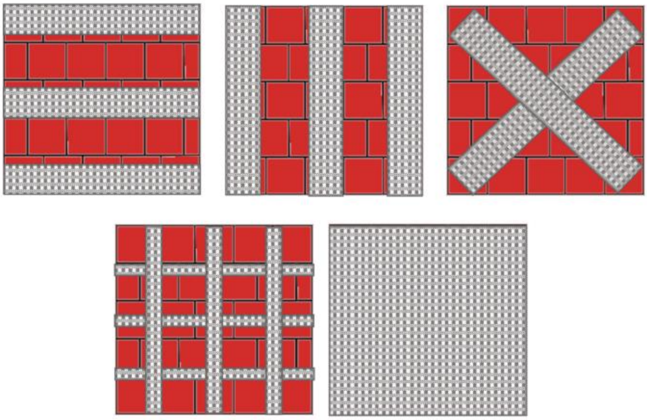

Figure. 13. Strengthening Layouts Of FRCM/TRM Application Over The Brick Masonry Wall (Thomoglou Et Al., 2023)

Base Isolation Systems

Base isolation is an innovative seismic mitigation technique involving the decoupling of a building from ground motions (Figure 14). Studies have shown that base isolation significantly reduces seismic forces transmitted to masonry structures, thereby preserving their integrity during earthquakes (Zani et al., 2019).

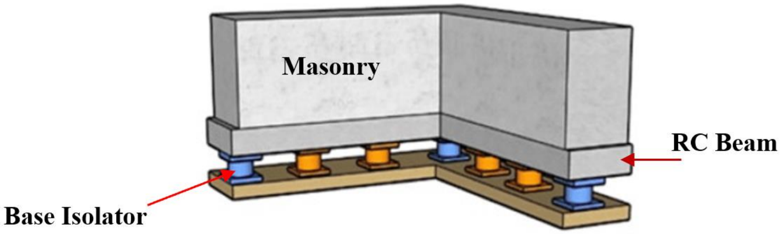

Figure 14: Strengthening Base Isolator Application On The Masonry (Usta, 2021)

COMPARATIVE ANALYSIS OF TECHNIQUES

Table 2 provides a comparative analysis of the discussed strengthening methods, summarizing their effectiveness, advantages, and limitations.

Table 2. Comparative Analysis Of The Discussed Strengthening Methods

Method	Effectiveness	Advantages	Limitations
Steel Reinforcement	High	Readily available, cost-effective	Corrosion risk, aesthetic impact
FRPs	Very High	Lightweight, corrosion-resistant	Sensitive to environmental factors
FRCMs	High	Compatible with masonry, heat-resistant	Limited research on long-term performance
Grouting	Moderate	Enhances bond, reduces water infiltration	Labor-intensive, scale limitations
Base Isolation	Very High	Effective seismic mitigation	High initial cost, complex implementation

CONCLUSIONS AND RECOMMENDATIONS

Masonry structures, due to their widespread use and historical significance, require tailored strengthening techniques to ensure their safety and longevity. The review highlights that traditional methods like steel reinforcement and grouting, alongside innovative approaches such as Fiber-Reinforced Polymers (FRPs) and Fiber-Reinforced Cementitious Matrices (FRCMs), have proven effective in enhancing the structural resilience of masonry buildings. Each method offers unique advantages and challenges, necessitating careful consideration of factors such as environmental conditions, material compatibility, and structural requirements.

Advanced modeling techniques, including Finite Element Analysis (FEM), play a critical role in optimizing these strengthening strategies, enabling more accurate assessments and effective designs. Observations from past seismic events underline the importance of integrating ductility-enhancing measures, such as horizontal and vertical reinforcements, to improve seismic performance.

Future efforts should focus on the development of hybrid strengthening systems that combine the strengths of traditional and modern techniques. Additionally, further research into the long-term behavior of these interventions under varying climatic and seismic conditions will be crucial. The adoption of such strategies will not only preserve the structural integrity of masonry buildings but also contribute to the sustainability of architectural heritage and safer urban environments.

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Seismic Damage Mechanisms Strategies For Historical Masonry Structures

Elifnur ŞAKALAK[1]

Ali Ekber SEVER[2]

Pınar Usta EVCİ[3]

1- Res. Asst. ; Isparta University of Applied Sciences, Faculty of Technology, Department of Civil Engineering elifnursakalak@isparta.edu.tr ORCID No: 0000-0002-8624-5337
2- Res. Asst. ; Isparta University of Applied Sciences, Faculty of Technology, Department of Civil Engineering alisever@isparta.edu.tr ORCID No: 0000-0001-5314-5287
3- Ass. Prof.. ; Isparta University of Applied Sciences, Faculty of Technology, Department of Civil Engineering pinarusta@isparta.edu.tr ORCID No: 0000-0001-9809-3855

ABSTRACT

Earthquakes pose significant risks to the structural integrity of buildings, particularly masonry structures, which have been widely used throughout history due to their accessibility and durability. However, their rigid and brittle nature makes them highly susceptible to seismic forces. This study examines the earthquake-induced damage mechanisms in masonry buildings, emphasizing the factors influencing their seismic performance. Common failure modes, including shear, flexural, and out-of-plane failures, are analyzed alongside the effects of soil conditions, material properties, and structural connections. The research also discusses the classification of earthquake damage based on severity and explores strategies for improving the earthquake resistance of masonry structures. The findings highlight the need for robust construction techniques, material selection, and retrofitting measures to enhance the resilience of these structures against seismic hazards. This study aims to provide a comprehensive understanding of the vulnerabilities of masonry buildings and propose effective mitigation strategies to reduce earthquake-related losses.

Keywords – Earthquake, masonry structures, seismic resistance, damage mechanisms, shear failure, flexural failure, connection weaknesses, soil effects, material properties, retrofitting methods, earthquake engineering.

INTRODUCTION

Natural disasters are defined as events that occur beyond human control and result in loss of life and property. These events are often sudden and unpredictable, making it extremely difficult to determine their exact time and location using current technology (Aral and Tunç, 2021; Alexander, 2018). Natural disasters are categorized based on geological, hydro-meteorological, biological, and socio-economic factors (Smith and Petley, 2009). Due to its geographical location, Turkey is highly susceptible to various natural disasters, including earthquakes, landslides, erosion, floods, rockfalls, and avalanches, all of which have caused significant destruction throughout history (Emre et al., 2018).

Earthquakes are among the most devastating natural disasters in Turkey, accounting for approximately 61% of all natural hazards in the country (TMMOB, 2012). Their sudden occurrence, unpredictability, and the inability to prevent them distinguish earthquakes from other disaster types (Kanamori, 2003). Due to its geographical location, Turkey lies on the Alp-Himalayan earthquake belt, one of the most seismically active zones in the world. The Anatolian Plate is surrounded by the Eurasian Plate to the north, the African and Arabian Plates to the south, the Eastern Anatolian Block to the east, and the Aegean Block to the west (Bikçe, 2015; Akbaş and Çalışkan 2023). This tectonic setting has resulted in three major fault systems in Turkey: the North Anatolian Fault (NAF), the East Anatolian Fault (EAF), and the Western Anatolian Graben System, all of which play a significant role in the country's seismic activity (Şaroğlu et al., 1992; Bozkurt, 2001).

According to Turkey's updated seismic hazard map (Figure 1), 96% of the country's land area is located in earthquake-prone zones, and 98% of the population resides in these high-risk regions (AFAD, 2023). Among these fault lines, the North Anatolian Fault is particularly active, having historically produced some of the most destructive earthquakes in the region. Given this high seismic risk, effective disaster management strategies and earthquake-resistant building designs are crucial to minimizing loss of life and property (Lourenço et al., 2020).

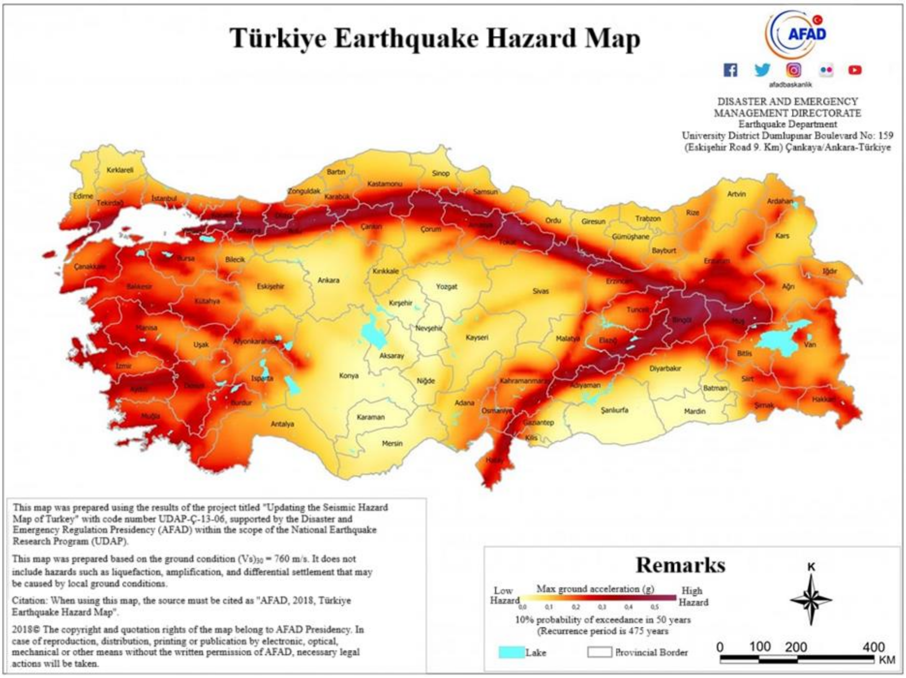

Figure 1: Seismic hazard map of Turkey (AFAD, 2023)

Turkey is an earthquake country and the fact that many earthquakes have occurred throughout history is proof of this. Table 1 shows some important earthquakes that occurred in Turkey.

Table 1: Some Important Earthquakes That Occurred in Turkey (Edemen, 2023).

Earthquake Name	Date	Location	Intensity	Magnitude	Death Toll	Injured
Hakkari Earthquake	6 May 30	Hakkari	Severe	7.2	2514	
Erzincan Earthquake	26 December 1939	Erzincan	Very Severe	7.9	32962	
Niksar/Erbaa Earthquake	20 December 1942	Niksar/Erbaa	Severe	7	3000	6300
Tosya/Ladik Earthquake	26 December 1943	Tosya/Ladik	Severe	7.2	2824	
Bolu/Gerede Earthquake	1 February 1944	Bolu/Gerede	Severe	7.2	3959	
Varto/Hınıs Earthquake	31 May 1946	Varto/Hınıs	Moderate		839	349
Varto Earthquake	19 August 1966	Varto	Severe	6.9	2394	1489
Gediz Earthquake	28 March 1970	Gediz	Severe	7.2	1086	1260
Lice Earthquake	6 September 1975	Lice	Severe	6.9	1385	3339
Çaldıran /Muradiye Earthquake	24 December 1976	Çaldıran/Muradiye	Severe	7.2	3840	497
Erzurum/Kars Earthquake	30 November 1983	Erzurum/Kars	Severe	6.8	1155	1142
Erzincan Earthquake	13 March 1992	Erzincan/Tunceli	Severe	6.8	653	3850
Dinar Earthquake	1 November 1995	Dinar	Moderate	5.9	94	
Ceyhan Earthquake	27 June 1998	Ceyhan	Moderate	6.3	84	310
Kocaeli Earthquake	17 August 1999	Kocaeli	Very Severe	7.4	17127	43953
Bolu/Düzce Earthquake	1999	Bolu/Düzce	Severe	7.2	845	4948
Çankırı Earthquake	2000	Çankırı	Moderate	6.1	2	1766

Afyon Earthquake	2000	Afyon	Moderate	5.8	6	547
Tunceli Earthquake	2003	Tunceli	Moderate	6.2	1	7
Bingöl Earthquake	2003	Bingöl	Severe	6.4	176	520
Erzurum Earthquake	2004	Erzurum	Moderate	5.1	9	20
Ağrı Earthquake	2004	Ağrı	Moderate	5.1	18	32
Hakkari Earthquake	2005	Hakkari	Moderate	5.5	2	5
Elazığ Earthquake	2010	Elazığ	Severe	6	51	74
Van Earthquake	23 October 2011	Van	Severe	7.2	604	4152
Van Earthquake (Aftershock)	9 November 2011	Van	Severe	5.6	40	260
Ege Sea Earthquake	20 July 2017	Ege Sea (Bodrum-Kos)	Moderate	6.6	2	120
Elazığ Earthquake	24 January 2020	Elazığ	Severe	6.7	41	1607
Izmir Earthquake	30 October 2020	Izmir	Severe	7	117	1034
Düzce Earthquake	23 November 2022	Düzce	Moderate	6.1	2	93
Kahramanmaraş Earthquake	6 February 2023	Kahramanmaraş	Extreme	7.8	50500	107204
Hatay Earthquake	20 February 2023	Hatay	Severe	6.4	6	294
Kütahya Earthquake	19.May.11	Kütahya/Simav	Moderate	5.9		
Van Earthquake	23 October 2011	Van	Severe	7.2	601	1966
Van Earthquake (Aftershock)	9 November 2011	Van/Edremit	Moderate	5.6		
Elazığ Earthquake	24 January 2020	Elazığ/Sivrice	Severe	6.8	41	1400
Izmir Earthquake	30 October 2020	Izmir/Seferihisar	Severe	6.6	116	1034
Kahramanmaraş Earthquakes	6 February 2023	Kahramanmaraş & 10 cities	Very Severe	7.7	50000	200000

Masonry structures are buildings that carry both horizontal and vertical loads through walls constructed using artificial or natural blocks bonded together with mortar (Bayülke, 2011). Throughout history, masonry structures have been widely used in various applications, including residential buildings, religious monuments, bridges, and defensive structures. However, their seismic performance varies significantly depending on material properties, construction techniques, and the dynamic characteristics of earthquake motion.

Due to their rigid nature, masonry structures have low energy dissipation capacity, making them highly susceptible to seismic forces (Döndüren, 2008). When subjected to large horizontal loads, these structures exhibit brittle behavior during an earthquake, as the materials used in their construction lack ductility. Consequently, sudden fractures and structural failures commonly occur, increasing their vulnerability to seismic damage.

EARTHQUAKE-INDUCED DAMAGE MECHANISMS IN MASONRY STRUCTURES

Masonry structures, among the oldest forms of construction, are built using locally sourced materials such as stone, adobe, and brick. These materials, while highly resistant to compression, exhibit brittle behavior with minimal ductility and are extremely weak under tensile forces. When subjected to high compressive loads, they become vulnerable to bending, shear, and tensile stresses, which they cannot effectively withstand. Despite enduring numerous seismic events and other natural disasters, many historic masonry buildings have survived over time and are now considered culturally significant structures requiring preservation. The seismic resilience of masonry buildings is influenced by several factors, including material properties, wall slenderness, and connection details. An increase in wall slenderness reduces a building’s earthquake resistance, meaning that shorter walls of the same thickness tend to perform better under seismic loads (Kaptan, 2010; Isın 2021).

Unlike reinforced concrete structures, where a clear distinction exists between load-bearing and non-load-bearing elements, masonry buildings rely entirely on their walls for structural stability. As a result, any damage directly impacts their overall integrity. Masonry walls are particularly sensitive to settlement-related deformations, with even minor foundation shifts leading to visible cracks and structural deterioration. This weakness stems from the brittle nature of masonry materials and their limited ability to sustain elastic stress before cracking. Additionally, due to the low strength of materials commonly used in masonry construction, these buildings are highly susceptible to damage, even under moderate loading conditions (Çoban, 2021).

The types of damage sustained by masonry structures during an earthquake vary depending on factors such as the rigidity of the load-bearing system, the adequacy of connection points, and the strength capacity of the walls. These types of damage can generally be classified as follows:

Structure Shear Failure

Shear damage is a type of damage that is seen especially in short and rigid walls. Earthquake forces create horizontal shear stresses on the structure, causing the walls to crack and break up. Shear cracks are usually seen as inclined cracks starting from the diagonal corners of the wall. The diagonal shear failure mechanism is illustrated in Figure 2.

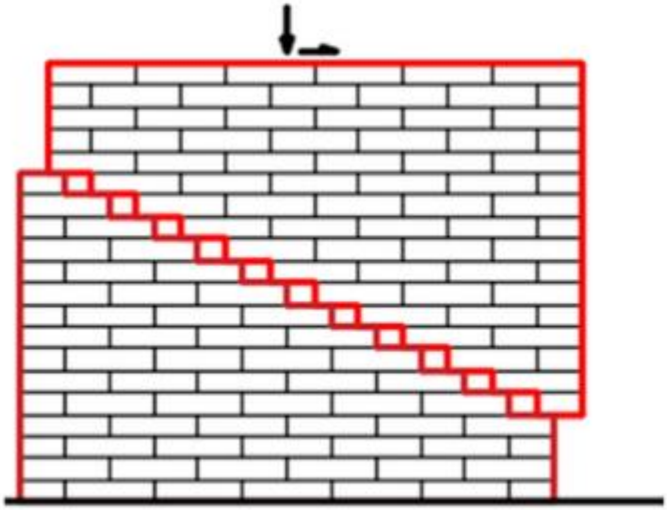

Figure 2: Diagonal shear failure (Kashani et. al. 2023)

Flexural Failure

In the event that the walls do not have sufficient horizontal rigidity during an earthquake, large moments occur in the lower or upper regions of the walls. This usually results in vertical cracks or the wall tipping outward or inward. Flexural failure is more common, especially in masonry structures with high walls or thin sections. The flexural failure mechanism is illustrated in Figure 3.

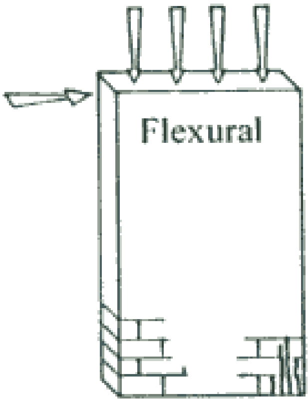

Figure 3: Flexural failure (Garbin et. al. 2007)

Connection Weaknesses

In the field of masonry structures, corner joints and connections between floors are of critical importance in determining the overall behaviour of the structure. Weaknesses in these areas can occur due to inadequate binders or poor workmanship, resulting in separations during seismic events. Such connection weaknesses can potentially lead to partial or complete collapse of the structure. The damage caused by weak connections at corners are illustrated in Figure 4.

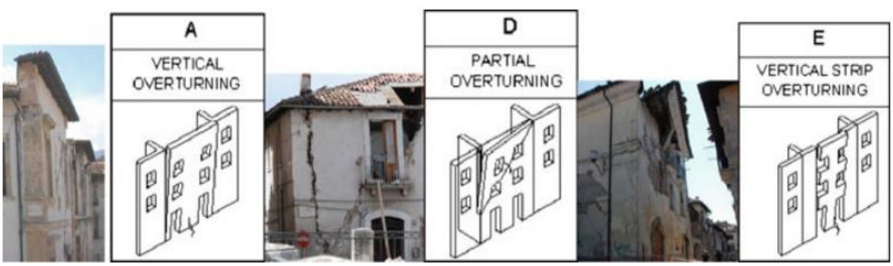

Figure 4: Damage caused by weak connections at corners; failure mechanism A, complete collapse of the facade; failure mechanism D, partial collapse along a diagonal; failure mechanism E, partial collapse of vertical strips of openings (D'Ayala and Paganoni, 2011)

Structural Damage Caused by Soil Conditions

Structural damage refers to the partial or complete loss of load-bearing capacity of a building or its elements due to external influences or human intervention. The extent of damage in a structure depends on factors such as the properties of load-bearing elements, the type of construction materials used, the characteristics of the ground, environmental conditions, and the speed at which external forces are transmitted to the structure.

The type of soil plays a crucial role in how seismic energy, released by the rupture of the Earth's crust, reaches a structure during an earthquake. The location of the building—whether it is on a transition zone between hard and soft soil, on a hillside, in a riverbed, on a fault line, in a landslide-prone area, or on reclaimed land—directly affects the level of damage that may occur due to seismic activity. Most soil-related structural issues arise from deficiencies in foundation design. During earthquakes, phenomena such as soil liquefaction, deformation in clayey soils, reduced bearing capacity due to insufficient foundation depth, lateral displacements, and loss of load-bearing strength in slender high-rise buildings are commonly observed. If the soil beneath a structure is weak or heterogeneous, it can lead to the formation of cracks, tilting, or differential settlements over time (Döndüren et. al. 2017).

Damage caused by soil conditions can often be identified by examining the location and orientation of cracks in a structure. For instance, if a building is supported by stable soil at both ends but has weak soil in the middle, wedge-shaped cracks may form, starting from the corners of door and window openings and extending outward at a 45-degree angle.

Preventing and mitigating soil-related damage falls within the field of geotechnical engineering and requires detailed soil investigations. Solutions such as soil reinforcement techniques or deep foundation systems reaching stable ground may be necessary to address these issues. However, these engineering interventions often involve high costs and complex technical procedures. The presence of a structure on an active fault line or on fractured bedrock significantly increases the risk of deterioration and collapse (Amman, 2012).

In masonry structures, settlement-related damage is often caused by the weakening of foundation soil, particularly clayey soils, due to water infiltration. Localized settlements beneath the foundation can lead to the formation of cracks in structural walls, posing a serious threat to the stability of the building. Figure 5 presents a schematic illustration of how such damages develop.

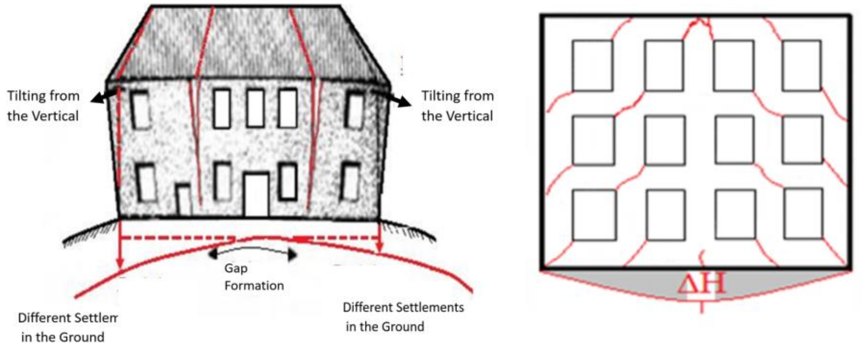

Figure 5: Diagram of Building Tilting and Settlement (Döndüren et. al. 2017)

Fracture Mechanisms in Masonry Structures

- ***Out-of-Plane Failure***

One of the most critical failure mechanisms of masonry structures during an earthquake is the outward toppling of walls when the earthquake load is perpendicular to the walls. This is usually due to inadequate tie beams or lack of stiffening elements. Such failures are prevalent, particularly in masonry structures with substantial spans, and can culminate in the complete collapse of the structure. The out-of-plane failure mechanisms are illustrated in Figure 6.

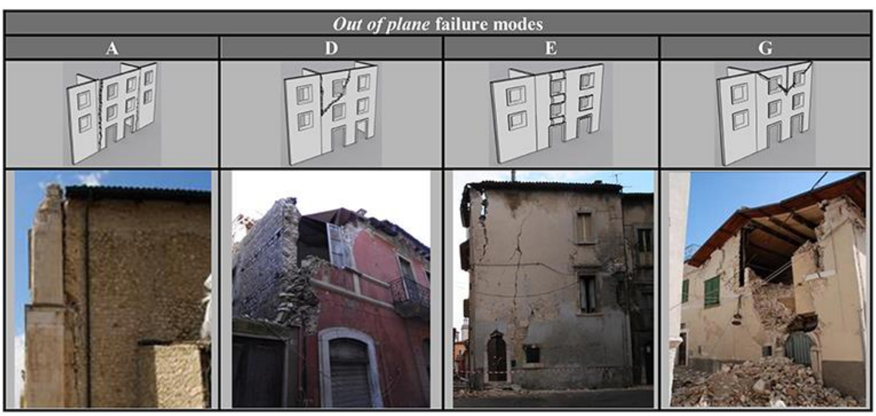

Figure 6: Out of plane failure modes (Novelli and D'ayala, 2019)

- ***In-Plane Failure***

Load-bearing walls resist in-plane lateral forces that occur during earthquakes, like shear walls. Shear cracks occur in load-bearing walls in the form of diagonal or inclined tension cracks. These cracks slide along the straight cracks at the horizontal ground connection points, creating cracks that gradually progress from the head connection points to the ground connection points (Günaydin et al., 2021; Yılmaz, 2024). The in-plane failure modes are illustrated in Figure 7.

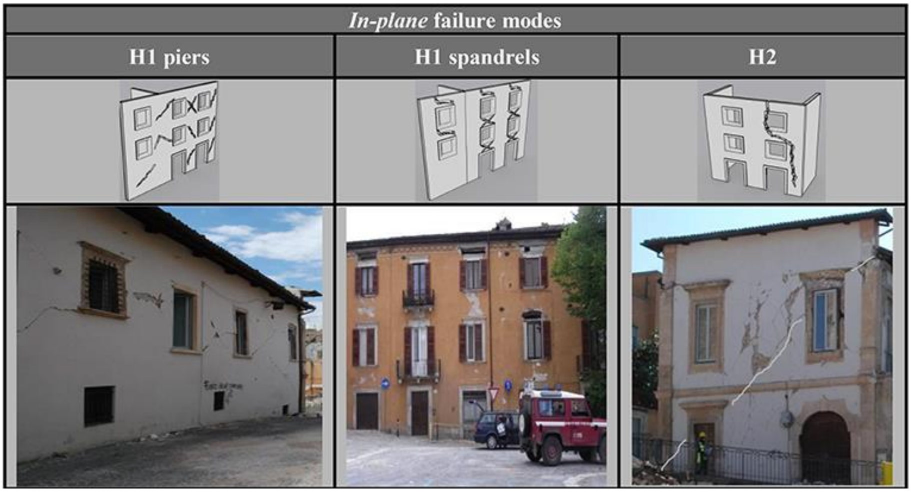

Figure 7: In plane failure modes (Novelli and D'ayala, 2019)

Material Deterioration and Micro-Cracks

Masonry structures usually consist of stone, brick and mortar. Over time, material deterioration occurs due to environmental effects. During an earthquake, such weaknesses further reduce the resistance capacity of the carrier system and accelerate the spread of cracks.

EARTHQUAKE DAMAGE GRADES IN MASONRY BUILDINGS

Workmanship plays an important role in the construction process and throughout the life of the structures. The resistance of masonry buildings to vertical loads and to horizontal loads of earthquakes depends on the geometry of the load-bearing walls, the strength of the preferred material and the method of joining the structural material used. Masonry buildings create large earthquake loads due to their heavy and rigid structures. Generally, the tensile strength of the wall material used in masonry structures is low, while the shear strength of the mortar is low. This situation causes damages such as cracks, separation and disintegration caused by tensile stresses as a result of the shear stresses formed in the walls during the earthquake. In addition, the non-ductile behavior of masonry buildings under tension and compression can cause the structure to collapse suddenly without showing a significant plastic deformation (Celep and Kumbasar, 2004; Arun, 2005; Çırak, 2011; Yılmaz, 2024).

The damages that occur are classified at different grades in terms of their effects on the structure.

- Slight Damage: Small-scale plaster cracks, plaster peeling and fine separations occur on wall surfaces. It does not damage the load-bearing system of the structure, but requires maintenance.
- Moderate Damage: Significant cracks and material losses occur in the load-bearing walls. Separations can be seen in the wall-floor junction areas. The structure needs to be reinforced.
- Heavy Damage: Shear cracks and wall separations reach serious dimensions. Deep and dense cracks occur. The load-bearing capacity of the structure is greatly reduced and carries the risk of collapse.
- Complete Damage (Collapse): Major losses occur in the load-bearing system of the structure, the walls collapse and the structure becomes completely unusable. It is usually not repairable and needs to be rebuilt.

As illustrated schematically in Figure 8, the degree of damage to masonry buildings is categorized as slight, moderate or heavy.

Figure 8: Examples of slightly, moderate and heavily damaged masonry buildings (Yılmaz et al., 2023)

In determining the damage levels in masonry buildings, the cracks that occur due to the load effect and their dimensions are used as the basic criteria. The methods developed for the damage detection of masonry structures after earthquakes are generally based on observation and the damage levels are determined according to the types of damage that occur. In this context, the damages that occur in masonry buildings are categorized according to the severity of the damage in the structure by Grünthal, 1998; Tomazevic, 1999; Corbane et al, 2011; Garcia et al. 2012 and Uros et al., 2020 (Figure 9).

	Masonry Buildings	Classification of Damages	Detailed Description
Grade 0		No Damage	
Grade 1		Negligible to slight damage - negligible structural damage, - slight non-structural damage	- Hair-line cracks in very few walls. - Fall of small pieces of plaster only. - Fall of loose stones from upper parts of buildings in very few cases.
Grade 2		Moderate damage (slight structural damage, moderate non-structural damage)	- Cracks in many walls. - Detachment of larger pieces of plaster. - Partial collapse of chimneys.
Grade 3		Substantial to heavy damage (moderate structural damage, heavy non-structural damage)	- Large and extensive cracks in most walls. - Roof tiles detach. - Failure of chimneys at roof level. - Failure of individual non-structural elements (partition walls, gable walls).
Grade 4		Very heavy damage (heavy structural damage, very heavy non-structural damage)	- Extensive failure of walls; partial structural failure of roofs and floors.
Grade 5		Destruction (very heavy structural damage)	- Total or nearly total collapse.

Figure 9: Damage degree in masonry buildings (Grünthal, 1998; Tomazevic, 1999; Corbane et al, 2011; Garcia et al., 2012; Uros et al., 2020)

FACTORS AFFECTING THE EARTHQUAKE RESISTANCE CAPACITY OF MASONRY BUILDINGS

The seismic performance of masonry buildings is contingent on various factors, including the geometry of their load-bearing walls, the properties of the materials utilised, and the construction techniques employed. The primary factors that influence the seismic performance of these buildings are as follows:

Material Properties

- ***Strength of stone, brick or mortar used***

The compressive, tensile and shear strengths of masonry walls constructed with different materials, such as brick, stone, briquette or concrete block, vary. Materials with low tensile and shear strengths in particular may exhibit brittle behaviour during an earthquake, which can result in structural damage.

- ***Mortar quality and binding properties***

The quality of the mortar that holds the wall elements together directly determines the integrity of the structure. The utilisation of mortar with inadequate strength can expedite the development of cracks in the walls during seismic events, potentially resulting in structural impairment. Moreover, masonry walls that are not adequately and completely jointed exhibit increased vulnerability to horizontal loads.

Geometric Factors

- ***Geometry of the walls***

The resistance of a structure to seismic activity is determined by the fundamental geometry of its load-bearing walls, namely their thickness, height, and length. Inadequate or disproportionate wall arrangements can result in wall deformations, such as buckling or toppling, during seismic events. Furthermore, deficiencies in wall connections within corner areas of a structure can compromise its integrity, increasing the susceptibility to damage.

- ***Total height of the building and floor layout***

Increasing the number of floors increases the earthquake forces to which masonry buildings are exposed, causing the structure to carry greater loads. Furthermore, disparities in stiffness between floors can cause the structure to oscillate unevenly during an earthquake, thereby compromising its structural integrity.

Mass and Center of Gravity of the Structure

Masonry buildings are typically characterised by their substantial mass and rigidity. These properties result in the occurrence of significant inertia forces during seismic events. In the event of an uneven distribution of mass or a centre of gravity that is not aligned with the geometric centre of the structure, the integrity of the structure can be compromised, leading to an augmentation in torsional effects.

Foundation System and Soil Conditions

Soil-structure interaction represents a pivotal factor in the context of seismic resistance in masonry structures. The presence of weak or unevenly settled soils can exert a deleterious effect on the structural rigidity, leading to the formation of cracks in the walls. The implementation of a robust foundation system, capable of maintaining stability during seismic events, enhances the overall safety of the structure and mitigates the risk of damage.

Structural Connections

In the context of masonry structures, it is imperative that the floor-wall and wall-wall joints are adequately robust. Inadequate connection details can result in the structural elements becoming dislocated from each other during seismic events, thereby compromising the integrity of the load-bearing system. The judicious design of elements such as joists, lintels and tie beams, in particular, enhances the seismic resistance of the structure, thereby ensuring its safety during seismic events.

Characteristics of Earthquake Motion

- ***Magnitude and duration of earthquake***

As the magnitude of an earthquake increases, so too do the forces acting on masonry structures. This results in increased stress on the structural system, thereby increasing the risk of damage. Furthermore, long-term seismic activity can subject structures to repeated loading, leading to the propagation of cracks and the weakening of structural elements due to fatigue.

- ***Effect of horizontal and vertical accelerations on the structure***

Horizontal accelerations represent a significant threat to the integrity of masonry structures, due to the limited resistance these structures offer to horizontal loads. In the absence of adequate fasteners, masonry structures may experience wall separation or toppling when subjected to horizontal accelerations. Vertical accelerations can also pose a risk, particularly for heavy and rigid masonry structures. In cases where foundation and wall connections are inadequate, vertical movements can result in the separation of structural elements, thereby compromising structural integrity.

- ***Nearby fault effect and waveforms coming to the structure***

Masonry structures are vulnerable to sudden and large accelerations caused by the effect of a nearby fault. In areas close to the fault line, seismic waves with high speed and acceleration can strain the strength capacity of the structure and cause sudden collapses. In addition, waveforms directly affect the vibration behavior of the masonry structure. Long-period waves create large amplitude oscillations in heavier and taller buildings, stressing the structure, while short-period waves cause sudden loading and can cause shear cracks in the walls.

CONCLUSIONS AND FUTURE RESEARCH

Masonry structures hold significant importance, particularly in terms of historical and cultural heritage. However, their seismic resistance varies greatly depending on the construction materials, building techniques, and prevailing soil conditions. The damage observed during earthquakes is often attributed to shear failure, flexural failure, or weaknesses at structural connections. Therefore, careful analysis and the implementation of strengthening methods are essential to enhance the seismic capacity of masonry structures.

Due to their material composition and geometric characteristics, masonry structures often exhibit brittle behavior during earthquakes. Investigations have revealed that these structures primarily suffer damage at connection points, wall-mortar joints, and areas with material weaknesses. The key factors determining the seismic resilience of masonry structures include material properties, wall thickness, building height, soil conditions, and connection details. In particular, the rigidity of load-bearing walls and the adequacy of connection details play a crucial role in ensuring seismic safety.

Furthermore, maintaining structural integrity requires a comprehensive approach that considers multiple parameters, from material selection to construction techniques. The durability of materials such as stone, brick, and mortar, along with the stability of walls and the effectiveness of load transfer mechanisms throughout the building, are critical in determining seismic performance. Additionally, designing foundation systems in accordance with soil conditions and ensuring sufficient connection details between structural elements are essential in preventing sudden collapses during seismic events.

In conclusion, a thorough understanding of the seismic behavior of masonry structures is essential for identifying effective mitigation strategies and developing safer structural designs. Future academic research and experimental studies will contribute to a deeper understanding of the structural vulnerabilities of masonry buildings and the development of innovative approaches for constructing more resilient structures against earthquakes.

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The Impact of Global Warming on Türkiye's Per Capita Water Amount: Analysis of Precipitation, Temperature and Evaporation Trends (2014–2024)

Yıldırım BAYAZIT[1]

1- Doç. Dr..; Bilecik Şeyh Edebali Üniversitesi Mühendislik Fakültesi İnşaat Mühendisliği Bölümü. yildirim.bayazit@bilecik.edu.tr ORCID No: 0000-0002-8699-4741

ABSTRACT

Over the past decade, Türkiye has experienced notable shifts in precipitation patterns, temperature increases, and evaporation rates, all of which have significantly impacted the nation's water resources. This research article examines these climatic parameters' trends and their effects on Türkiye's per capita water amount between 2014 and 2024. According to the findings of the study, Türkiye is under water stress according to the Falkenmark index. Projections predict that the country will enter the water scarcity category in the next five years.

Keywords – climate change impact, meteorological data, water resources, Türkiye

INTRODUCTION

Global warming, driven by anthropogenic factors such as fossil fuel consumption, industrial activities, and land-use changes, is characterized by rising global average temperatures and disruptions to climate systems. Global warming has significantly altered climatic parameters, including temperature, precipitation patterns, and intensity, evaporation rates, and the frequency of extreme weather events, with profound implications for water resources. Rising global temperatures, driven by anthropogenic greenhouse gas emissions, have accelerated hydrological cycles, leading to increased evaporation and atmospheric moisture content, which in turn amplify precipitation variability (IPCC, 2021). This manifests as intensified droughts in arid regions (e.g., the Sahel and Mediterranean) and more extreme rainfall events in humid zones, exacerbating flood risks (Held & Soden, 2006). Snowpack reduction and glacial retreat, particularly in the Himalayas and Andes, threaten the seasonal meltwater supply critical for river systems serving billions (Immerzeel et al., 2020). Concurrently, altered precipitation regimes disrupt groundwater recharge, reducing the resilience of aquifers to over-extraction (Taylor et al., 2013). These changes diminish water resource potential, with global freshwater availability projected to decline by 20% by 2050 under high-emission scenarios (World Bank, 2016). Compounded by population growth, water scarcity is intensifying: per capita water availability has already fallen by over 60% since 1960, with 3.2 billion people living in water-stressed regions (UN Water, 2021). Regions reliant on glacial or snowmelt-dependent rivers, such as South Asia, face acute risks to agricultural and urban water security (Shrestha et al., 2015). Additionally, rising temperatures degrade water quality through increased algal blooms and pollutant concentration, heightening health risks (Mishra et al., 2021). These cascading effects underscore the urgency of adaptive water governance frameworks to mitigate inequities in water access and ensure sustainable management amid climatic uncertainty (Vörösmarty et al., 2000).

Türkiye, due to its geographical location in the Mediterranean basin, semi-arid climate zone, and topographical diversity, is particularly vulnerable to the impacts of global warming. Systematic observations over the past decade (2014–2024) reveal striking shifts in Türkiye's climatic parameters. Mersin et al. (2022) reported that annual average temperatures increased by 0.20-0.35 °C/decade, based on data from 14 stations in the Aegean region. Toros et al. (2017) revealed that the rise of 0.94°C in average annual temperature over the long period of 1912–2016 under impacts of anthropogenic climate change in Istanbul. Winter rainfall in the Mediterranean and Aegean regions has decreased by up to 15%, while extreme rainfall events in the Black Sea region have become more frequent (IPCC, 2023). In addition, Çelebioğlu et al. (2024) revealed that there was a decrease in the annual total precipitation trend in all regions of Turkey except the Black Sea region, according to the precipitation data covering the years 1968-2018. It is known that evaporation increases with increasing temperatures and irregular precipitation regimes. Bağdatlı and Arıkan (2020) observed that there is an increasingly significant trend in the monthly total and maximum open surface evaporation data between 1978-2019 in Niğde province of Türkiye. Türkiye, with its developing economy and growing cities, is on its way to becoming "water poor" (WWF, 2014). Karataş (2024) determined that the relationship between Turkey's usable freshwater resources and large deviations in population due to intense migration will push the country's resources below the water scarcity line in the future.

While existing literature focuses on factors limiting Türkiye's climate adaptation capacity (e.g., gaps in water management policies, urbanization pressures), studies holistically analyzing parametric changes over the past decade remain limited. This study aims to present how climate parameters such as precipitation, temperature and evaporation have affected the amount of water per capita in Türkiye in the last decade, and how this situation will progress, together with sustainable policy solutions.

1. METHODOLOGY

In this study, Türkiye was studied as the research area. Türkiye is a transcontinental country straddling Southeastern Europe and Western Asia, bordered by the Black Sea to the north, the Mediterranean Sea to the south, and the Aegean Sea to the west (Figure 1).

Figure 1: Location of the study area

This study uses Türkiye's climate parameters such as annual precipitation, temperature and evaporation for the last decade and calculates their trend with a linear regression line. At the same time, this study also calculates the per capita water amount of the country by analyzing the available data with the water budget method. Thus, it is aimed to reveal the impact and change of the country's existing water resources on the per capita water amounts in the last decade. The values of the climatic parameters used in this study were obtained from the reports of the General Directorate of Meteorological Affairs, which are freely and publicly available (DMİ, 2025). Population data for the last ten years of the country was obtained from the reports published by the Turkish Statistical Institute, also free of charge (TUİK, 2025).

2. RESULTS

Precipitation Trends

When the annual total precipitation data for the years 2014-2024 are analyzed, it is seen that there has been a decreasing trend in the last decade (Figure 2). While 641.6 mm of annual precipitation was observed in 2014, 567 mm of precipitation was observed in 2024. It is calculated that there is an 11.6% decrease in precipitation compared to ten years ago. In addition, the average of precipitation data for the last ten years is 593.34 mm. In this ten-year period, it was observed that 5 years (2017, 2020, 2021, 2022, 2024) received precipitation below the average of 10 years. The downward trend of global warming on precipitation in the last decade in Türkiye can be clearly seen. While rainfall averages are decreasing, sudden extremes in the rainfall regime are also observed. Sudden and heavy rainfall also causes floods (Hekimoğlu and Altındeğer, 2008).

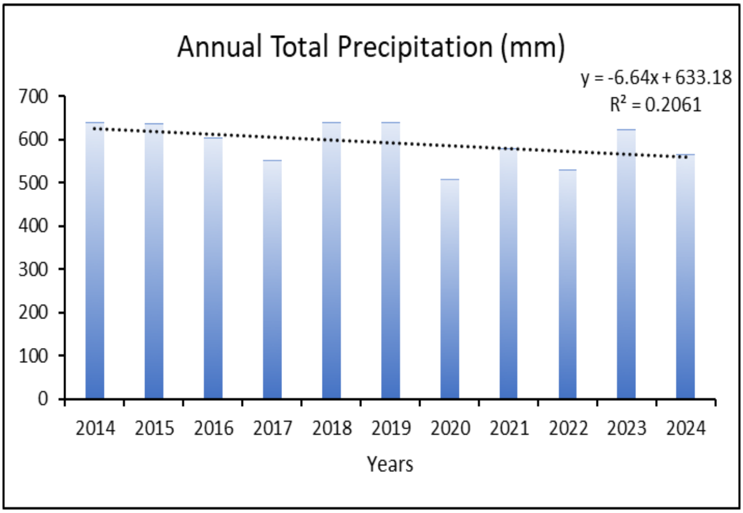

Figure 2: Annual total precipitation of Türkiye (2014-2024)

Temperature Trends

Analysis of annual average temperature data from 2014 to 2024 reveals a persistent warming trend over the past decade (Figure 3). The mean temperature increased from 14.5°C in 2014 to 15.3°C in 2024, representing a 5.52% rise compared to the baseline decade. The decadal average temperature for this period was calculated at 14.44°C. Notably, six years (2014, 2018, 2020, 2021, 2023, 2024) exhibited temperatures exceeding the 10-year mean, with 2023 and 2024 marking consecutive record-breaking anomalies. This acceleration aligns with global climate models projecting intensified warming under anthropogenic forcing (IPCC, 2023), underscoring the urgency of climate mitigation strategies.

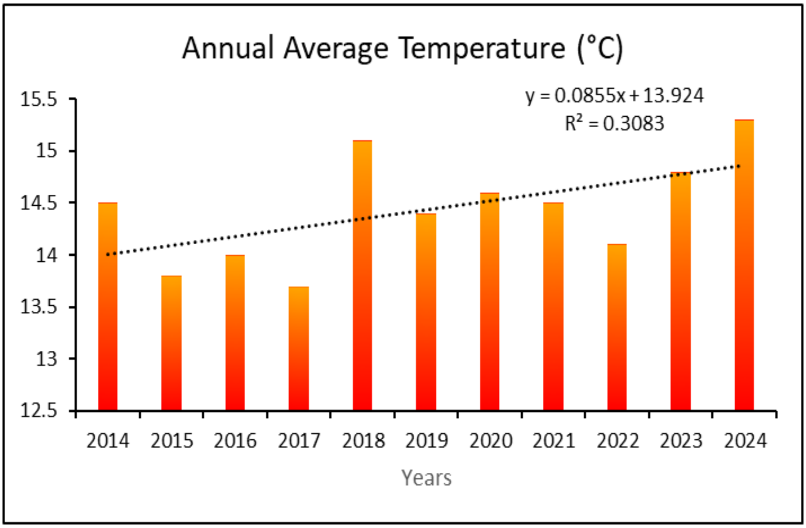

Figure 3: Annual average temperatures of Türkiye (2014-2024)

Evaporation Rates

Temperature and evaporation are inseparable parameters. Zhou, H., et al. (2015) reported in his study that the increase in earth has caused a increase in lake evapotranspiration. Analysis of daily evaporation data from 2014 to 2024 reveals an increasing evaporation trend over the last decade (Figure 3). The daily evaporation value increased from 5.6 mm in 2014 to 6 mm in 2024, representing an increase of 7.14% compared to the initial decade. The ten-year average daily evaporation for this period is 5.96 mm. Six years in particular (2017, 2019, 2020, 2021, 2022, 2024) exhibited evaporation exceeding the 10-year average.

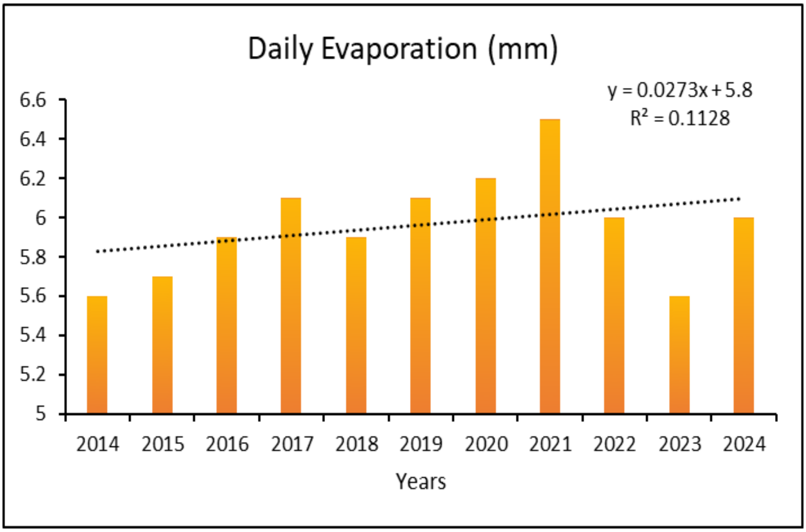

Figure 4: Daily average evaporation of Türkiye (2014-2024)

4. DISCUSSION

While examining the changes in precipitation, temperature and evaporation climate parameters in Türkiye in the last decade, it is very important to observe how they affect the available water potential and the amount of water per capita in order to provide a holistic approach to the issue. Therefore, there is a need to calculate the net water potential using the water budget method. Using the precipitation and evaporation values for 2014-2024, the net water potential of the country was calculated by years, taking into account the groundwater reserve and infiltration losses. Then, the calculated net water potentials were divided by the population and the amount of water per capita was calculated for the last ten-year period on a yearly basis. All calculations are shown in Table 1.

Table 1: Calculations of water potential

Years	Inputs		Losses		Population (Number of Person)	Area (km^2)	Net Water Potential (m^3)	Water Potential Per Capita (m^3/year)
	Precipitation (m^3)	Ground water (m^3)	Evaporation (m^3)	Infiltration (m^3)				
2014	$502.73x10^9$	$14x10^9$	$258.32x10^9$	$41x10^9$	$77.70x10^6$	783562	$217.41x10^9$	2798.23
2015	$499.76x10^9$		$262.94x10^9$		$78.74x10^6$		$209.82x10^9$	2664.69
2016	$474.60x10^9$		$272.16x10^9$		$79.82x10^6$		$175.44x10^9$	2198.11
2017	$433.62x10^9$		$281.39x10^9$		$80.81x10^6$		$125.24x10^9$	1549.75
2018	$500.85x10^9$		$272.16x10^9$		$82.00x10^6$		$201.69x10^9$	2459.53
2019	$501.25x10^9$		$281.39x10^9$		$83.16x10^6$		$192.86x10^9$	2319.25
2020	$397.74x10^9$		$286.00x10^9$		$83.61x10^6$		$84.74x10^9$	1013.41
2021	$454.23x10^9$		$299.84x10^9$		$84.68x10^6$		$127.39x10^9$	1504.39
2022	$415.37x10^9$		$276.77x10^9$		$85.28x10^6$		$111.59x10^9$	1308.54
2023	$489.65x10^9$		$258.32x10^9$		$85.37x10^6$		$204.33x10^9$	2393.34
2024	$444.28x10^9$		$276.77x10^9$		$85.67x10^6$		$140.51x10^9$	1640.17

When the per capita water amount values of Türkiye in the last decade are analyzed, it is seen that the value decreased from 2798.23 m^3 in 2014 to 1640.17 m^3 in 2024. This situation reveals a loss of approximately 41.39%. If we consider the ten-year period separately in two periods, the average of the years (2014-2019) is 2331.59 m^3 while the average of the years (2020-2024) is 1571.97 m^3. This shows that Türkiye has experienced water stress in the last 5 years according to the Falkenberg indicator (Falkenberg, 1986).

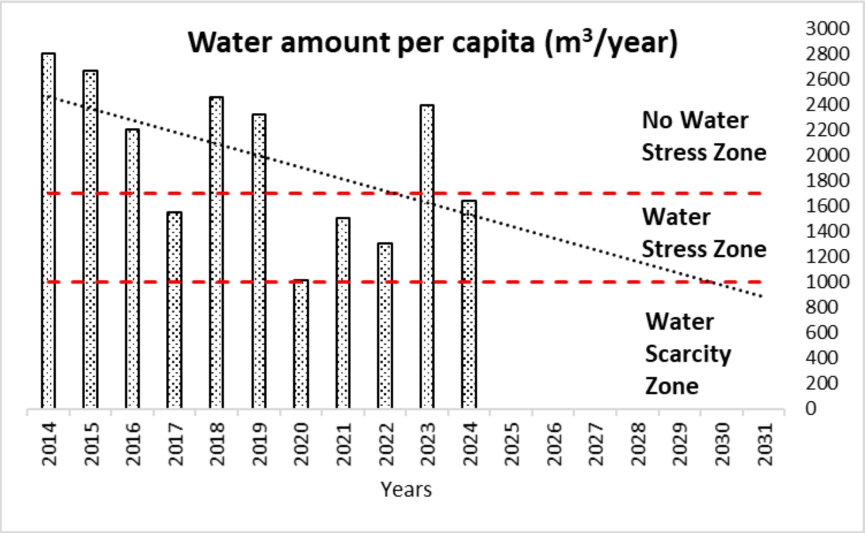

Figure 5: Estimation of water availability of Türkiye

As seen in Figure 5, when the linear regression trend line of the per capita water amount values is extended, the date when Türkiye will transition to the Water Scarcity zone according to the Falkenberg scale is determined as 2030. Considering that precipitation is in a decreasing trend while temperatures and evaporation are in an increasing trend, it is seen that water per capita tends to decrease dramatically with increasing population. In order to take precautions against all this negative situation, it is necessary to reduce carbon emissions, unconditional compliance with climate change protocols, and sustainable water management policies should be implemented and followed by decision makers.

CONCLUSION

The past decade has seen significant climatic changes in Türkiye, with declining precipitation, rising temperatures, and increased evaporation rates adversely affecting water resources. These trends highlight the urgency for adaptive water management practices and the development of policies aimed at mitigating the impacts of climate change on Türkiye's hydrological systems.

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