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Enhancing the stability of retaining walls through Kevlar reinforcement

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Abstract

Retaining walls are widely used to support soil masses and protect roads, railways, buildings, and other infrastructure against lateral earth pressure. Controlling their deformation is essential for maintaining serviceability and reducing the risk of cracking and progressive deterioration. This study presents a preliminary analytical investigation into the effect of incorporating 5% Kevlar fibers into concrete used for retaining wall panels. The effective elastic modulus of ordinary and Kevlar-reinforced concrete was estimated using a mixture-law approach, while an analytical formulation was applied to evaluate the displacement-to-height ratio of wall panels with heights ranging from 1 to 7 m. The results show that the addition of Kevlar increases the elastic modulus from 30 to 32.6 GPa, corresponding to an improvement of approximately 8.67%. A consistent reduction in the displacement ratio was also observed for all the wall heights considered. For example, at a height of 7 m, the ratio decreased from 0.00063 for ordinary concrete to 0.00058 for Kevlar-reinforced concrete. These findings indicate that Kevlar fibers may improve the stiffness and deformation resistance of concrete retaining wall panels. However, the present results are analytical and preliminary. Experimental validation, numerical modeling, durability assessment, and soil–structure interaction analysis are required before practical application.

Keywords: Retaining walls, Kevlar reinforcement, Concrete, Elastic modulus, Displacement behavior.

1. Introduction

Retaining walls are essential civil engineering structures used to support soil masses and protect roads, railways, buildings, urban areas, and other infrastructure

JIRRS
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Pages: 1-13

systems. Their main role is to resist lateral earth pressure and limit soil movement. Their performance depends on several factors, including wall geometry, material stiffness, soil characteristics, drainage conditions, foundation behavior, and soil–structure interaction. Excessive deformation may lead to cracking, loss of alignment, serviceability problems, and gradual deterioration. Improving the stiffness and deformation resistance of retaining wall components therefore remains an important objective in structural and geotechnical engineering.

The development of advanced cement-based materials has created new opportunities to improve the behavior of concrete structures. In recent years, researchers have incorporated fibers, mineral additions, recycled materials, metallic particles, and nanoparticles into concrete to enhance its mechanical, thermal, and dynamic properties. Harrat et al. (2021), for example, investigated the static behavior of nano-SiO_2-based concrete beams resting on an elastic foundation, while Mohammed et al. (2022) analyzed the bending response of nano-SiO_2-reinforced concrete slabs. Other studies examined the use of glass powder, Fe_2O_3 nanoparticles, nano-clay platelets, and related inclusions to improve the bending, buckling, vibration, and thermomechanical behavior of concrete beams, slabs, and panels (Benfrid et al., 2023; Dine Elhennani et al., 2023; Chatbi et al., 2023; Harrat et al., 2023; Kecir et al., 2024).

The behavior of composite and advanced structural elements under different loading conditions has also received considerable attention. Chatbi et al. (2022) studied the free-vibration response of carbon-nanotube-reinforced composite beams resting on elastic foundations. Benbakhti et al. (2024) proposed an analytical approach for evaluating the hydrostatic bending of advanced composite materials. Other investigations demonstrated the contribution of advanced materials to structural stiffness, thermal performance, mechanical resistance, and stability-related behavior in plates, panels, concrete walls, and bridge elements (Benfrid and Bouiadjra, 2024; Khetir et al., 2024; Benfrid et al., 2025; Abderrahmane et al., 2025; Al-Ani et al., 2025).

More recent studies by Benfrid and co-authors have focused on the mechanical, thermal, and dynamic characterization of eco-concretes and heterogeneous composite materials. These works mainly use analytical and numerical homogenization techniques to estimate the effective properties of materials containing mineral, metallic, bio-derived, or nanoscale inclusions. Such techniques are useful because the overall response of a composite depends not only on the individual properties of its constituents, but also on the concentration, size, distribution, and interaction of the inclusions within the surrounding matrix.

Benfrid et al. (2026) applied the Mori–Tanaka homogenization scheme to concrete reinforced with aluminum powder. Their study evaluated the influence of aluminum inclusions on the effective mechanical behavior of the composite. Kahlouche et al. (2026) developed an analytical predictive model for assessing the mechanical and thermal characteristics of concrete walls containing pumice powder. Their results highlighted the potential of lightweight mineral additions to improve the

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Pages: 1-13

multifunctional performance and environmental sustainability of cement-based materials.

Related investigations extended these approaches to other materials and structural applications. Benfrid (2026) examined the local instability of polymer plates reinforced with nanocomposite materials, with particular attention to the influence of material heterogeneity on structural response. A biphasic homogenization model was also proposed to predict the thermal and mechanical properties of eco-concretes by treating concrete as a two-phase material whose effective behavior is governed by the interaction between the matrix and the inclusions.

Mohammedi et al. (2026) investigated the effective mechanical properties of eco-concretes reinforced with bio-sourced calcium carbonate nanoparticles. The resulting material properties were coupled with a free-vibration analysis of simply supported slabs, establishing a relationship between nanoscale reinforcement and structural dynamic response. In another contribution, Mohammedi et al. (2026) analyzed sustainable concrete reinforced with bio-derived nano-$CaCO_3$ and applied the obtained elasto-nano-mechanical properties to the free-vibration analysis of raft foundations. Their study emphasized the possibility of improving structural performance while reducing the environmental impact associated with conventional concrete. Benfrid (2026) also investigated the elastomechanical behavior of concrete containing aluminum nano-inclusions and discussed the influence of inclusion type, size, and concentration on its effective elastic properties.

Taken together, these investigations show that advanced inclusions and homogenization methods can improve the understanding and prediction of concrete behavior. However, most previous studies have focused on beams, slabs, plates, panels, bridge decks, or foundations. Comparatively less attention has been given to the use of advanced fiber-reinforced concrete in retaining wall panels, particularly for improving stiffness and controlling lateral deformation.

Retaining wall design and stability have been widely discussed in geotechnical engineering. Guerrin and Lavaur (1976) provided classical procedures for the design and calculation of reinforced-concrete retaining walls and quay walls. Bouafia (2018, 2019) presented important contributions concerning the stability and regulatory design of rigid retaining walls. Djadouni et al. (2015) investigated the environmental use of waste tires behind retaining walls, while Abe (2022) examined seismic reinforcement methods for leaning-type retaining walls. Acharya et al. (2023) also discussed cost-effective techniques for monitoring infrastructure and detecting structural changes. Although these studies provide an important basis for retaining wall analysis, the contribution of high-performance fibers to the material response of retaining wall panels remains insufficiently explored.

Among the fibers used in cementitious materials, Kevlar has attracted increasing interest because of its high tensile strength, low density, impact resistance, and resistance to conventional electrochemical corrosion. These properties may make Kevlar useful in applications where crack control, stiffness, and deformation

JIRRS
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Pages: 1-13

resistance are important. Nevertheless, its incorporation into concrete may also involve practical limitations related to cost, workability, fiber dispersion, interfacial bonding, and long-term durability in the alkaline cementitious environment.

Previous studies have demonstrated the potential of Kevlar fibers in concrete and concrete-like materials. Wang and Hu (2016) reported the benefits of short Kevlar fibers at the interface of repaired concrete-like materials. Li et al. (2023a) compared the mechanical behavior of carbon-, Kevlar-, and hybrid-fiber-reinforced concrete under quasistatic and dynamic loading conditions. Li et al. (2023b) further investigated Kevlar-fiber-reinforced concrete under static and high-strain-rate loading. Al-Daraji and Aljalawi (2024) studied the effect of Kevlar fibers on lightweight perlite concrete, while Mola et al. (2024) examined the combined use of Kevlar and steel fibers in concrete pavements. These studies indicate that Kevlar may improve tensile resistance, crack control, stiffness, and deformation behavior. However, its specific application to retaining wall panels has not yet been sufficiently investigated.

From a structural mechanics perspective, the elastic modulus directly influences the flexural rigidity of a structural element. Under the same loading and geometric conditions, an increase in elastic modulus generally leads to a reduction in elastic deflection. It is therefore reasonable to investigate whether the incorporation of Kevlar fibers can reduce the deformation of concrete retaining wall panels. However, reduced displacement should not be interpreted as proof of complete retaining wall stability, since global stability also depends on sliding, overturning, bearing capacity, drainage, foundation conditions, and soil–structure interaction.

Accordingly, the present work provides a preliminary analytical investigation of the influence of incorporating 5% Kevlar fibers into concrete used for retaining wall panels. Ordinary concrete is compared with Kevlar-reinforced concrete by estimating the effective elastic modulus through a mixture-law approach and evaluating wall deformation using an analytical deflection formulation. The main objective is to determine whether the stiffness increase associated with Kevlar reinforcement produces a consistent reduction in the displacement-to-height ratio for different wall heights.

The main contribution of this study lies in connecting the effective elastic properties of Kevlar-reinforced concrete with the serviceability-related deformation response of retaining wall panels. The analysis is not intended to provide a complete retaining wall design or a definitive recommendation for field application. Rather, it offers an initial theoretical basis for future experimental and numerical investigations involving different Kevlar contents, realistic lateral earth-pressure distributions, nonlinear material behavior, drainage conditions, foundation flexibility, durability, and soil–structure interaction.

JIRRS
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Pages: 1-13

2. Formulations

The present study provides a preliminary analytical assessment of the influence of Kevlar fibers on the stiffness and displacement response of concrete retaining wall panels. The wall is idealized as a vertical cantilever panel fixed at its base and subjected to the same lateral loading conditions in both the ordinary-concrete and Kevlar-reinforced cases. The comparison is therefore based only on the change in the effective elastic modulus of the material.

The following assumptions are adopted:

- the concrete and Kevlar fibers behave linearly within the elastic range;
- the Kevlar fibers are uniformly distributed within the concrete matrix;
- perfect bonding and load transfer between the fibers and concrete are assumed;
- small-deformation theory is applicable;
- the geometry, loading conditions, support conditions, and cross-sectional moment of inertia remain unchanged;
- cracking, creep, shrinkage, drainage effects, foundation flexibility, and nonlinear soil–structure interaction are not considered;
- the Kevlar content of 5% refers to the volume fraction of fibers in the composite.

These assumptions define the study as a first-order analytical investigation rather than a complete retaining-wall design analysis.

The effective elastic modulus of Kevlar-reinforced concrete is estimated using a modified rule of mixtures:

$$E_f = E_c * V_c + E_K * V_K$$

Within the linear-elastic range, the lateral displacement of a structural panel is inversely proportional to its flexural rigidity, EI. For a given wall geometry, lateral load, and support condition, the displacement may be expressed in the general form (Bouafia, 2018):

$$f = \frac{ph^3}{30EI}$$

The proposed formulation evaluates only the influence of the effective elastic modulus on the deformation response of the wall panel. It does not represent a complete assessment of retaining-wall stability. Sliding, overturning, bearing-

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Pages: 1-13

capacity failure, cracking, reinforcement yielding, hydrostatic pressure, drainage conditions, foundation flexibility, and nonlinear soil–structure interaction are outside the scope of the present analysis. Consequently, the results should be interpreted as preliminary estimates requiring experimental and numerical validation before practical design application.

3. Results and discussions

Effective elastic modulus : The effective elastic modulus calculated for ordinary concrete and concrete containing 5% Kevlar fibers is presented in Table 1. The ordinary concrete has an elastic modulus of 30 GPa, whereas the value estimated for Kevlar-reinforced concrete is 32.6 GPa.

Table 1. Effective elastic modulus between ordinary concrete and concrete with 5% Kevlar.

Vf (%)	The elastic modulus (GPa)
0	30
5	32.6

The addition of 5% Kevlar increases the estimated elastic modulus by approximately 8.67%. This increase results from the higher elastic modulus of the Kevlar fibers compared with the concrete matrix. Under the assumptions of uniform fiber distribution and perfect interfacial bonding, part of the applied load is transferred from the concrete matrix to the fibers, leading to a stiffer composite material.

This result is consistent with the general behavior reported for Kevlar-reinforced cementitious materials, in which the fibers can contribute to stiffness, tensile resistance, and deformation control. However, the modulus obtained in this study is based on an idealized mixture-law model. It should therefore be considered a theoretical estimate rather than a directly measured material property. In an actual concrete mixture, fiber orientation, agglomeration, porosity, workability, and fiber–matrix bonding may reduce the effective contribution of Kevlar.

The calculated increase in elastic modulus is moderate rather than exceptional. Nevertheless, even a moderate increase may be useful in structural components where serviceability and displacement control are important. This is particularly relevant for retaining wall panels, which are continuously subjected to lateral loading.

Displacement response:The displacement-to-height ratios were calculated using the relationship between elastic modulus and flexural rigidity. Since the geometry,

JIRRS
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DOI: 10.66104/bmzjan61
Pages: 1-13

loading, moment of inertia, and boundary conditions are kept unchanged, the displacement of the Kevlar-reinforced panel is obtained by multiplying the reference displacement by the stiffness ratio is 0.92.

The theoretical displacement reduction is therefore approximately 7.98% for all wall heights. Table 2 presents the corrected displacement values using this consistent stiffness ratio.

Table 2. Comparison between Ordinary Concrete and Concrete with 5% Kevlar.

H(m)	1	2	3	4	5	6	7
f/h [20]	0.00009	0.00018	0.00027	0.00036	0.00045	0.00054	0.00063
f/h [Present] 5% of Kevlar	0.00008	0.00016	0.00025	0.00034	0.00042	0.00049	0.00058

The displacement ratio increases with wall height for both materials. This trend is expected because taller wall panels are more flexible and generally undergo greater lateral deformation under comparable loading conditions. However, the Kevlar-reinforced concrete produces lower displacement values throughout the investigated height range.

For a wall height of 1 m, the estimated displacement decreases from approximately 0.090 to 0.083 mm. At 4 m, the displacement decreases from 1.440 to 1.325 mm. The largest absolute difference occurs at 7 m, where the displacement is reduced from approximately 4.410 to 4.058 mm. Although the absolute reduction at 7 m is only about 0.352 mm, the trend remains consistent.

The reduction can be explained directly by the increase in flexural rigidity. For a structural panel with unchanged geometry, the flexural rigidity is defined by the product EI. Since the second moment of area I remains constant, increasing the elastic modulus from 30 to 32.6 GPa increases EI by 8.67%. As displacement is inversely proportional to flexural rigidity in the adopted linear-elastic model, the resulting reduction in displacement is approximately 7.98%.

This relationship confirms the internal consistency between the calculated material properties and the wall response. The reduction is not an independent numerical observation; it follows directly from the increase in the effective elastic modulus.

From a serviceability perspective, the reduction in lateral displacement obtained with Kevlar-reinforced concrete may help limit visible cracking, loss of alignment, excessive movement of the supported soil, and possible damage to nearby structures. For a wall height of 7 m, the displacement-to-height ratio decreases from

JIRRS
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Pages: 1-13

0.00063 for ordinary concrete to 0.00058 for Kevlar-reinforced concrete. These values correspond approximately to H/1587 and H/1725, respectively. The higher denominator obtained for the Kevlar-reinforced panel indicates a lower normalized deformation and therefore a modest but measurable improvement in displacement control. However, these values should not be interpreted as direct proof of compliance with a specific design code, since acceptable displacement limits depend on the wall type, soil conditions, drainage system, construction method, nearby structures, and project-specific serviceability requirements.

The calculated improvement is directly related to the assumed contribution of the Kevlar fibers. The initial model uses an efficiency factor of η=1, corresponding to ideal fiber orientation, uniform dispersion, and perfect load transfer between the fibers and the concrete matrix. Since such conditions may not be fully achieved in practice, a sensitivity analysis was carried out using lower efficiency factors. When η is reduced to 0.80, the effective elastic modulus decreases to 31.78 GPa, corresponding to a modulus increase of 5.93% and an estimated displacement reduction of 5.60%. For η=0.60, the effective modulus becomes 30.96 GPa, with a modulus increase of 3.20% and a displacement reduction of approximately 3.10%. In the ideal case of η=1.00, the modulus reaches 32.60 GPa and the predicted displacement reduction is 7.98%. These results show that the expected improvement depends strongly on fiber efficiency. Therefore, the value of 32.6 GPa should be considered an idealized upper-bound estimate rather than a guaranteed material property. Experimental measurements are required to determine a realistic efficiency factor for the selected Kevlar fibers and concrete mixture.

The findings are generally consistent with previous studies reporting that Kevlar fibers can improve selected mechanical properties of concrete and concrete-like materials. Wang and Hu (2016) observed beneficial effects of short Kevlar fibers at the interface of repaired concrete-like materials. Li et al. (2023a, 2023b) showed that Kevlar reinforcement can influence the mechanical response of concrete under quasistatic, dynamic, and high-strain-rate loading. Al-Daraji and Aljalawi (2024) also reported changes in the mechanical behavior of lightweight perlite concrete containing Kevlar fibers, while Mola et al. (2024) examined the use of Kevlar in hybrid fiber-reinforced concrete pavements. Unlike these previous investigations, the present work links the estimated effective elastic modulus of Kevlar-reinforced concrete to the displacement behavior of retaining wall panels. Its contribution is therefore mainly analytical and focused on serviceability. Nevertheless, direct numerical comparison with previous studies remains difficult because of differences in concrete composition, fiber dimensions, dosage, orientation, loading conditions, and experimental procedures.

Although the analytical results indicate an improvement in stiffness, the practical incorporation of 5% Kevlar fibers by volume may present several challenges. A relatively high fiber content can reduce concrete workability and increase the risk of fiber agglomeration. Poor dispersion may create weak zones and limit effective load transfer between the matrix and the fibers. Kevlar is also generally more expensive than conventional steel or polypropylene fibers, and its economic feasibility should

JIRRS
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Pages: 1-13

be evaluated in relation to the expected structural benefit. Other important aspects include the quality of the fiber–matrix interface, the effect of the alkaline cement environment, moisture exposure, and long-term durability. These factors may significantly influence the actual performance of Kevlar-reinforced concrete.

The present analysis does not consider compressive strength, tensile strength, cracking, post-cracking behavior, creep, shrinkage, fatigue, or durability. Consequently, the calculated increase in elastic modulus should not be used alone to conclude that all the mechanical and durability properties of the concrete will improve. The results only indicate that, within the assumptions of the model, Kevlar fibers may increase effective stiffness and reduce elastic displacement.

The findings should therefore be regarded as preliminary. They are derived from an analytical homogenization model rather than experimental testing or detailed finite-element simulations. The model assumes linear-elastic behavior, small deformations, uniform fiber distribution, perfect bonding, and identical geometry and loading for both materials. It does not account for concrete cracking, reinforcement yielding, nonlinear soil pressure, hydrostatic pressure, drainage conditions, foundation flexibility, construction stages, or soil–structure interaction. Moreover, the reduction in panel displacement does not demonstrate complete retaining wall stability against sliding, overturning, bearing-capacity failure, or deep-seated soil failure. In this study, improved performance refers specifically to increased effective stiffness and reduced elastic deformation.

Kevlar-reinforced concrete should therefore be considered a promising material for further investigation rather than a fully validated solution for retaining wall construction. Future research should include experimental characterization of concrete mixtures containing different Kevlar percentages, workability and fiber-dispersion tests, direct measurements of elastic modulus, flexural and tensile testing, durability assessment, and numerical modeling of complete retaining wall systems under realistic soil, water, foundation, and loading conditions.

4. Conclusion

This study presented a preliminary analytical investigation into the effect of incorporating 5% Kevlar fibers by volume into concrete used for retaining wall panels. The effective elastic modulus was estimated using a modified rule-of-mixtures approach, while the displacement response was evaluated under identical geometrical, loading, and boundary conditions for ordinary and Kevlar-reinforced concrete.

The results showed that the addition of Kevlar increased the estimated elastic modulus from 30 to 32.6 GPa, corresponding to an improvement of approximately 8.67%. This increase in stiffness produced a consistent theoretical reduction of about 7.98% in the displacement-to-height ratio over the investigated wall-height range of 1–7 m. At a wall height of 7 m, for example, the displacement ratio decreased from 0.00063 for ordinary concrete to approximately 0.00058 for Kevlar-

JIRRS
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Pages: 1-13

reinforced concrete. These findings indicate that Kevlar fibers may contribute to better elastic deformation control in concrete retaining wall panels.

However, the results should be interpreted within the limits of the analytical model. The calculated modulus of 32.6 GPa is based on ideal assumptions of uniform fiber distribution, effective orientation, and perfect bonding between the fibers and the concrete matrix. The sensitivity analysis showed that lower fiber efficiency would lead to smaller improvements in stiffness and displacement control. The study also considered only linear-elastic wall-panel deformation and did not evaluate cracking, creep, shrinkage, reinforcement yielding, nonlinear soil pressure, drainage effects, foundation flexibility, or soil–structure interaction.

Therefore, the reduction in displacement reported in this work should not be considered evidence of complete retaining wall stability against sliding, overturning, bearing-capacity failure, or deep-seated soil failure. Instead, it provides an initial indication that Kevlar-reinforced concrete may be a promising material for improving the stiffness and serviceability behavior of retaining wall panels.

Further research should include experimental characterization of concrete containing different Kevlar percentages, direct measurement of elastic and mechanical properties, workability and fiber-dispersion tests, durability assessment, and detailed finite-element modeling of complete retaining wall systems under realistic soil, water, foundation, and loading conditions. Such investigations are necessary before Kevlar-reinforced concrete can be recommended for practical retaining wall applications.

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