Revue des Composites et des Matériaux Avancés-Journal of Composite and Advanced Materials
Vol. 36, No. 2, April, 2026, pp. 363-374
Journal homepage: http://iieta.org/journals/rcma

Introduction of Recycled Tile Waste Sand in the Formulation of Diss Fiber-Reinforced Mortar: Durability Study and Statistical Modeling

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https://doi.org/10.18280/rcma.360212

Received: 12 February 2026
Revised: 10 April 2026
Accepted: 17 April 2026
Available online: 30 April 2026

Keywords:
mortar, Diss fibers, sand, tile waste, characterizations, durability, full factorial design

ABSTRACT

This study investigates the valorization of tile waste within a circular economy framework by using recycled tile sand (TS) as a partial substitute for natural sand in Diss fiber (Ampelodesmos mauritanicus) reinforced mortar. The objective is to enhance durability performance while reducing the environmental impact associated with construction waste disposal and excessive sand extraction. Natural sand was replaced with recycled tile waste sand at substitution rates of 15%, 30%, and 50%. An experimental program was conducted to evaluate key durability parameters, including water absorption by immersion and capillarity, chemical resistance under acidic solutions (5% HCl, 5% H_2SO_4, 5% CH_3COOH) and saline exposure (5% NaCl), as well as chloride ion penetration depth. To complement the experimental investigation, a statistical analysis was performed using single-factor regression and two-factor full factorial models with first-order linear interactions, in order to compare the measured durability properties with the predictions of the regression models. The results obtained confirm the beneficial effect of incorporating recycled sand on durability, particularly through reduced chloride penetration and improved resistance to saline and acidic environments, especially at 15% substitution, except under H_2SO_4 exposure. Furthermore, the statistical analysis demonstrated satisfactory predictive accuracy of the developed models, with good agreement between experimental and predicted values. Significance tests (p-values < 0.05) identified exposure time as the dominant factor for most durability responses, while the influence of recycled sand content was response-dependent, being statistically significant for capillary absorption and sulfuric acid attack. Interaction effects between variables were generally non-significant, indicating limited combined influence on the studied responses.

1. INTRODUCTION

Mortar reinforced with natural fibers such as hemp, palm, wood, and particularly Diss fibers represents an innovative, eco-friendly, and sustainable alternative to conventional construction materials [1]. Incorporating these plant-based fibers into the cementitious matrix significantly enhances the mechanical performance of the mortar, especially its tensile and flexural strength, while increasing ductility [2-4]. The fibers act as crack-bridging elements: they restrict crack propagation, delay brittle failure, and thereby promote a tougher material response.

Moreover, natural fibers help mitigate shrinkage-induced cracking, improving the dimensional stability of the mortar. Their low density contributes to reducing the overall weight of the material, while their porous structure imparts beneficial thermal and acoustic properties. As a result, these mortars are particularly well-suited for applications where insulation capacity and environmental performance are key requirements [5].

Thus, Diss fiber-reinforced mortar offers a promising solution within a sustainable construction framework, combining mechanical performance with environmental benefits. It also contributes to the valorization of natural resources and to the reduction of the carbon footprint associated with the production of synthetic materials [6].

The valorization of recycled aggregates in mortars reinforced with natural fibers constitutes an innovative and sustainable approach aimed at reducing the exploitation of natural resources and limiting the environmental impact of the construction sector. By partially or totally substituting natural aggregates with aggregates derived from construction and demolition waste, it becomes possible to preserve quarry resources, decrease energy consumption related to extraction and transportation, and significantly reduce the carbon footprint of cement-based materials [7-11].

This strategy fully aligns with the principles of the circular economy, in which construction waste is reintroduced into the production cycle as new raw materials. Consequently, the reuse of recycled aggregates not only limits the volume of waste sent to landfill but also transforms these residues into high-value-added resources [12].

Combining recycled aggregates with natural fibers (hemp, palm, wood, Diss, etc.) further enhances the ecological character of the material [13]. While recycled aggregates reduce the overall environmental impact, natural fibers improve the mechanical performance of the mortar, particularly tensile strength, ductility, and crack control. This synergy yields a more resilient and lighter material, with potentially improved thermal and acoustic performance.

However, the incorporation of recycled aggregates, particularly tile waste originating from construction and demolition activities or manufacturing plants, may influence certain mortar properties, such as water absorption, porosity, and mechanical strength. These effects are often attributed to the possible presence of adhered old mortar or to a rougher surface texture [14]. Therefore, optimized mix design and rigorous control of recycled aggregate characteristics are essential to ensure satisfactory performance. In summary, the combined use of recycled aggregates and natural fibers in mortar represents a promising pathway toward the development of more sustainable construction materials, reconciling technical performance, waste reduction, and the preservation of natural resources.

The objective of this work is to introduce recycled sand derived from tile waste as a partial substitute for crushed natural sand in the formulation of a mortar reinforced with Diss natural fibers, and then to evaluate the influence of this substitution on durability-related parameters. In addition, this research seeks to simplify the analysis of the experimental results and to identify the key factors affecting the selected responses. To achieve this objective, the experimental results were analyzed using a combination of statistical approaches. Single-factor regression models were applied when only one variable influenced the response, whereas a two-factor full factorial design with first-order linear regression models, including interaction terms, was employed when both recycled sand content and exposure time were considered. This approach enables a systematic evaluation of the individual and combined effects of multiple factors on the responses of interest. The analysis relies on statistical tools to interpret the experimental data and to identify the factors that significantly influence the studied outcomes [15, 16].

2. MATERIALS CHARACTERISATION

The binder used was a Portland composite cement CPJ CEM II 42.5 (S–L), supplied by the Hdjar Soud cement plant (Skikda). This cement is characterized by a nominal compressive strength of 42.5 MPa at 28 days. It contains supplementary additions of ground granulated blast furnace slag (S) and limestone (L).

The plant fibers (F) used in this study were derived from the Diss plant, harvested in the mountainous region of Skikda province (Algeria). After extraction, the plant material was manually cut into fibers with an average length of 2.5 cm. To enhance their adhesion to the cementitious matrix and to remove impurities as well as soluble substances likely to interfere with cement hydration, the fibers were treated in boiling water for 20 minutes, the treated fibers exhibit a density of 700 kg/m³ and a high water absorption capacity of approximately 61%, they also present a tensile strength of 100 MPa and an elastic modulus of about 1300 MPa [7].

A quarry sand (QS) with a particle size class of 0/4 was used as fine aggregate. It was sourced from the Ben Brahim quarry located in Constantine. This natural sand exhibits a grading curve suitable for mortar formulation and contributes to achieving good compactness, satisfactory workability, and adequate mechanical performance.

The tile sand (TS) used in this study originated from tile off-cuts and rejected pieces collected from construction sites and processing workshops (Figure 1). These wastes, initially in the form of fragments of varying sizes, were subjected to mechanical crushing to reduce their particle size. The crushed material was subsequently sieved to obtain a 0/4 granular fraction equivalent to natural sand, suitable for mortar production. Figure 2 presents the different materials used in this study.

Table 1 summarizes the properties of the natural and recycled sand–TS. The chemical analyses were carried out using X-ray fluorescence (XRF). The particle size distribution curves of the two sands are shown in Figure 3.

Figure 1. Tile waste

Figure 2. Used materials

Table 1. Properties of ordinary and recycled sands

Properties	Quarry Sand (QS)	Tile Sand (TS)
Apparent density (g/cm^3)	1.450	1.745
Absolut density (g/cm^3)	2.620	2.618
Methylene blue (%)	0.7	0.5
Sand equivalent (%)	61	83
Water absorption (%)	2.00	3.85
CaO (%)	55.55	51.10
Al_2O_3 (%)	0.18	0.92
Fe_2O_3 (%)	0.08	0.35
SiO_2 (%)	0.13	3.80
MgO (%)	0.25	1.01
Cl- (%)	0.04	--

According to the results of the physical characterization tests, the absolute densities of the two types of sand are practically identical, indicating a generally comparable mineralogical nature and allowing for substitution without significant alteration of the solid volume in the mix design.

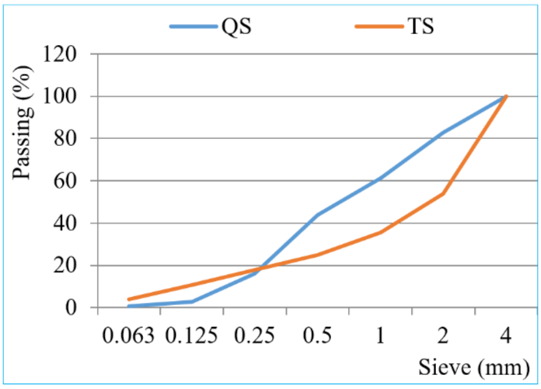


Figure 3. Particle size distribution curve of the sands

Note: QS = quarry sand, TS = tile sand

However, the particle size analysis reveals a notable difference: The sand derived from tile waste has a fineness modulus of 3.56, classifying it as relatively coarse sand, whereas the natural sand has a fineness modulus of 2.93, characteristic of medium sand. This difference reflects a higher proportion of coarse particles in the recycled sand. Nevertheless, both sands exhibit a particle size distribution within the standardized range, indicating an acceptable grain distribution for construction applications. However, the particle size distribution of natural sand is better than that of recycled sand. A well-graded particle size distribution leads to a more compact and stronger mortar, while also improving its resistance to aggressive environments as well as its other durability parameters.

The recycled sand also has a higher content of fines. This increased presence of fine particles can help improve the compactness of the mix by filling the voids between coarser grains. The sand equivalency test, an indicator of cleanliness and clay content, shows that the recycled sand is actually cleaner than the natural sand, with a low percentage of clay fines, which minimizes adverse effects on paste–aggregate bonding and durability.

The water absorption coefficient of the recycled sand (3.8%) is slightly higher than that of the natural sand (2%). This difference can be attributed to the presence of adhered old mortar on the crushed tile particles, as reported by Benhalilou et al. [7] and Kherraf et al. [14]. This characteristic may influence both the mechanical performance and the durability of the mortars.

Chemical analyses further indicate that the CaO content of the recycled sand (51.10%) is lower than that of the natural sand (55.55%). Calcium oxide plays a key role in cohesion at the matrix–aggregate interface [17], contributing to adhesion mechanisms and chemical bonding with the cement paste. The CaO promotes the formation of expansive products and dissolves readily in acidic environments [18].

3. EXPERIMENTAL PROGRAM

3.1 Mix design

In this study, the natural sand in a fiber-reinforced mortar was partially replaced with recycled sand derived from tile waste. The control mix (0%) corresponds to a fiber-reinforced mortar whose reference formulation was established in previous studies [7]. In this base formulation, one-third (1/3) of the natural sand volume is substituted with an equivalent volume of Diss plant fibers. Building on this base composition, additional mixes were prepared by partially replacing the natural sand with recycled TS at substitution rates of 15%, 30%, and 50% by volume. For all mixes studied, the parameters kept constant were the cement dosage, water content, and Diss fiber content, in order to isolate the effect of the recycled sand on mortar performance. The different mix compositions considered in this study are summarized in Table 2.

Table 2. Mix compositions

Mortar	Cement	Quarry Sand (QS)	Fibers (F)	Tile Sand (TS)	Water (W)
0%	1 V	2/3 V	1/3 V	0	1 V
15%	1 V	85% to 2/3 V	1/3 V	15% to 2/3 V	1 V
30%	1 V	70% to 2/3 V	1/3 V	30% to 2/3 V	1 V
50%	1 V	50% to 2/3 V	1/3 V	50% to 2/3 V	1 V

Note: V: Volume

3.2 Conducted tests

Water absorption by immersion was measured in accordance with EN 1015-10 on specimens with dimensions of 4 × 4 × 16 cm^3. The specimens were oven-dried at 105 °C until a constant mass (Ms) was achieved. They were then fully immersed in water at a temperature of 20 °C for 24 hours, after which their saturated mass (Mh) was determined. The water absorption coefficient by immersion (Ab) was calculated using Eq. (1).

$$\mathrm{Ab} = \frac{\mathrm{Mh} - \mathrm{Ms}}{\mathrm{Ms}} \times 100\% \qquad (1)$$

Water absorption by capillarity was determined in accordance with EN 1015-18 on specimens measuring 4 × 4 × 16 cm^3, previously cured in water for 28 days at 20 ± 1 °C. After sealing the lateral faces, the initial mass (M_0) was recorded. The specimens were then subjected to one-dimensional capillary absorption by immersing their bottom face in a constant water depth of 3 mm. The mass gain, resulting from capillary rise of water, was measured at regular time intervals. Capillary absorption was expressed as a function of the square root of time, according to Eq. (2).

$$\mathrm{I} = \frac{\Delta \mathrm{M}}{\mathrm{A}} \qquad (2)$$

where, I is the absorbed water per unit surface area (g/cm^2), ΔM is the mass gain (kg), and A is the cross-sectional area of the immersed face (cm^2).

Chemical resistance: the chemical resistance of the mortars in acidic and saline environments was assessed according to ASTM C267-96. Tests were conducted on cubic specimens measuring 5 × 5 × 5 cm^3. After demolding, the specimens were stored in water for 28 days at a temperature of 20 ± 1 °C to achieve full hydration. At the end of this period, the initial mass (M_0) of each specimen was recorded. The samples were then immersed in different aggressive solutions: 5% hydrochloric acid (HCl), 5% sulfuric acid (H_2SO_4), 5% acetic acid (CH_3COOH), and 5% sodium chloride (NaCl). The solutions were renewed every 7 days according to pH variations. The mass of each immersed specimen (M_i) was measured at different exposure intervals, namely 3, 7, 14, 21, 28, 56, and 90 days (Three specimens were tested for each variant). Chemical resistance was evaluated through mass variation (weight loss or gain, M (%)), calculated using Eq. (3).

$$\mathrm{M}\ (\%) = \frac{M_i - M_0}{M_0} \times 100 \tag{3}$$

Chloride ion penetration: chloride ion penetration in accordance with the UNI 7928 and JIS A 1171 standards was evaluated at 28 days on prismatic specimens measuring 4 × 4 × 16 cm^3. After demolding, the specimens were stored in water for 28 days to ensure adequate hydration at a temperature of 20 ± 1 °C. Following this curing period, the specimens were coated on their lateral surfaces with a layer of paraffin to ensure unidirectional chloride ion penetration. They were then immersed in a 5% NaCl solution (three specimens were tested for each variant). After the planned exposure duration, the samples were cut into half-prisms. The freshly cut surface was then sprayed with a silver nitrate ($AgNO_3$) solution to highlight the chloride ion penetration depth, which was determined by observing the resulting color contrast.

4. RESULTS AND DISCUSSION

4.1 Water absorption by immersion

The incorporation of tile waste as a substitute for natural sand leads to a reduction in water absorption, irrespective of the substitution rate (Figure 4). The minimum value is observed at a 15% substitution rate. However, beyond this threshold, increasing the proportion of recycled sand results in a progressive rise in absorption, reaching higher values at 50% substitution. This behavior can be attributed to the presence of adhered old mortar on the crushed tile particles, which promotes higher porosity and, consequently, a greater water absorption capacity [14].

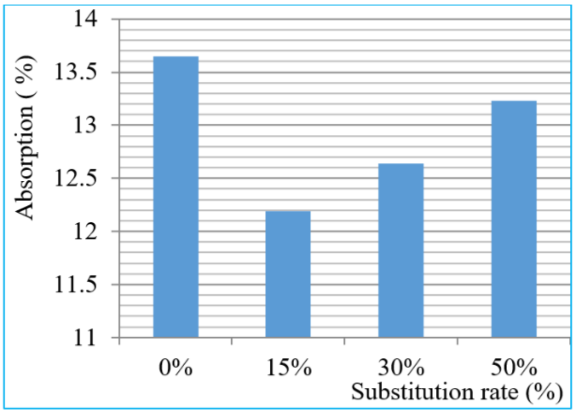


Figure 4. Variation of water absorption by immersion as a function of the substitution rate

4.2 Water absorption by capillarity

The curves plotted as a function of the selected exposure times (Figure 5) exhibit a similar increasing trend. The results indicate that capillary absorption rises proportionally with immersion duration. However, mortars incorporating recycled sand consistently show lower capillary absorption values than the control mortar at all investigated time intervals. The reduction in capillarity can be attributed to the decreased porosity resulting from the filling of voids by the fines present in the recycled sand, which improves the compactness of the matrix. Moreover, the presence of adhered old mortar on the grains, characterized by higher water porosity than QS, gives the recycled sand a higher water absorption capacity. This increased absorption effectively lowers the water-to-cement (w/c) ratio [7, 19, 20], thereby limiting the amount of free water able to penetrate the capillary pores of the material.

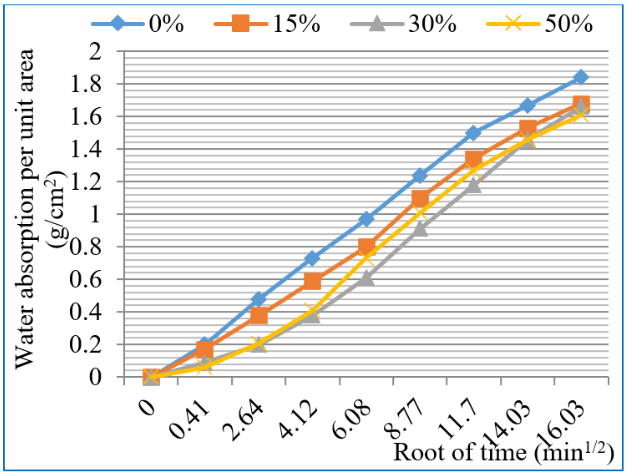


Figure 5. Variation of capillary absorption as a function of time

4.3 Chemical attack by hydrochloric acid (HCl)

The evolution of mass loss of mortars exposed to a 5% HCl solution at 3, 7, 14, 21, 28, 56 and 90 days (Figure 6) shows that mortars incorporating recycled sand exhibit lower mass loss than the control mortar, which consistently records the highest values at all investigated ages. Acid attack is primarily attributed to the reaction between portlandite, $Ca(OH)_2$, and the acidic medium, leading to the formation of soluble calcium chloride ($CaCl_2$) and the progressive dissolution of the cementitious matrix. The mortar containing 15% recycled sand shows the lowest mass loss compared with those incorporating 30% and 50% recycled sand. This trend may be explained by the presence of old mortar residues adhering to the recycled particles. These residues, rich in $Ca(OH)_2$, react with HCl ions, which can intensify dissolution processes and result in additional mass loss as the substitution rate increases [21].

4.4 Chemical attack by sulfuric acid (H_2SO_4)

The incorporation of recycled sand derived from tile waste leads to a significant reduction in mass loss compared with the control mortar (Figure 7). Indeed, the maximum mass loss is recorded for the mortar made with natural sand. This higher vulnerability may be attributed to the presence of free lime (CaO) in the natural sand, which weakens the cementitious matrix and reduces its chemical resistance in aggressive environments [22]. Mortars incorporating 30% and 50% recycled sand exhibit a similar trend and demonstrate the best resistance performance under sulfuric acid (H_2SO_4) exposure.

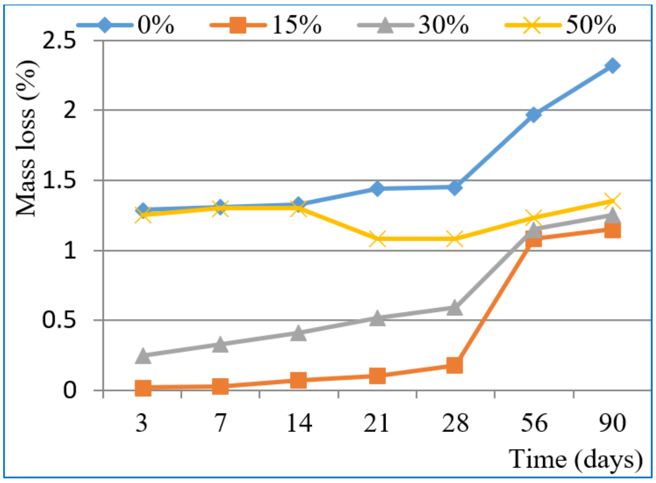


Figure 6. Mass loss as a function of immersion period in 5% HCl

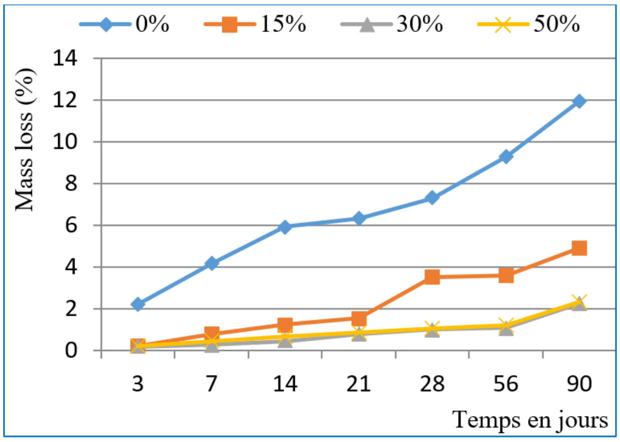


Figure 7. Mass loss as a function of immersion period in 5% H_2SO_4

4.5 Chemical attack by acetic acid (CH_3COOH)

Mortars containing recycled sand derived from tile waste show the lowest mass losses in the CH_3COOH solution (Figure 8), indicating good resistance in this aggressive medium. The best performance is observed for the mortar incorporating a 15% substitution rate, with a more pronounced improvement compared with the 30% and 50% substitution levels. These results can be explained by the beneficial effect of the fines present in the recycled sand, which contribute to pore filling and densification of the cementitious matrix. At the optimal substitution rate of 15%, these fines enhance compactness and may also participate in secondary pozzolanic reactions, promoting additional calcium silicate hydrate (C–S–H) formation and reducing mortar permeability [23]. By contrast, at higher substitution levels (30% and 50%), increased porosity, possible microstructural heterogeneity, and the progressive degradation of hydration products may lead to reduced resistance to acid attack, resulting in greater mass loss [24].

4.6 Chemical attack by sodium chloride (NaCl)

Immersion of the mortars in a 5% NaCl solution results in a mass gain for all mixes, with only slight variations between substitution levels (Figure 9). Mortars incorporating recycled tile waste sand exhibit the lowest mass gains, indicating better resistance to chemical attack. These results can be explained by the formation of secondary compounds such as chloroaluminates (Friedel's salt), produced by the reaction between Cl^- ions and the aluminate phases of cement. These products may partially block the pore network and limit the subsequent penetration of chloride ions [14, 25]. The best performance is recorded for the mortar containing 15% recycled sand. The presence of fines improves compactness and densifies the cementitious matrix, thereby reducing porosity and permeability. Enhanced compactness and the increased formation of secondary calcium silicate hydrate (C–S–H) may further restrict chloride ion ingress and improve the durability of mortars incorporating recycled tile waste sand.

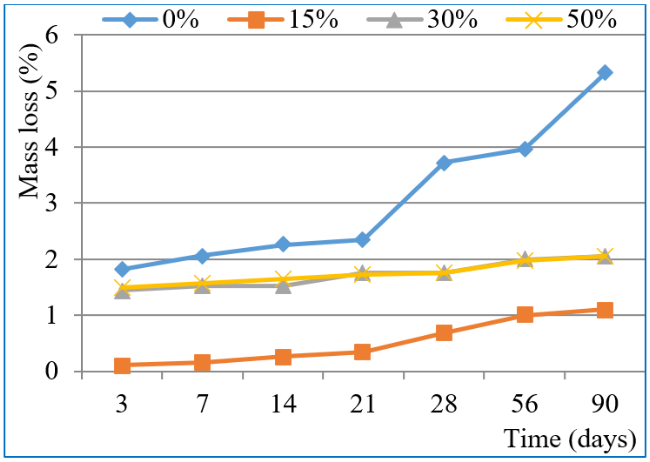


Figure 8. Mass loss as a function of immersion period in 5% CH_3COOH

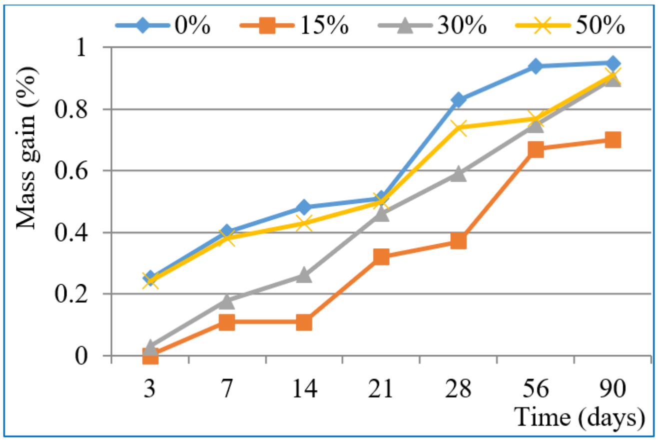


Figure 9. Mass gain as a function of immersion period in 5% NaCl

4.7 Chloride penetration

For all substitution rates, the depth of chloride ion penetration decreases when recycled tile waste sand is used (Figure 10). The minimum value is observed at a substitution rate of 15%. This trend can be attributed to the high cleanliness of the recycled sand and the absence of clay impurities, which promote better mortar compactness. As a result, capillary porosity is reduced and preferential ion transport pathways are limited, leading to lower permeability and reduced chloride ion migration within the cementitious matrix [26, 27].

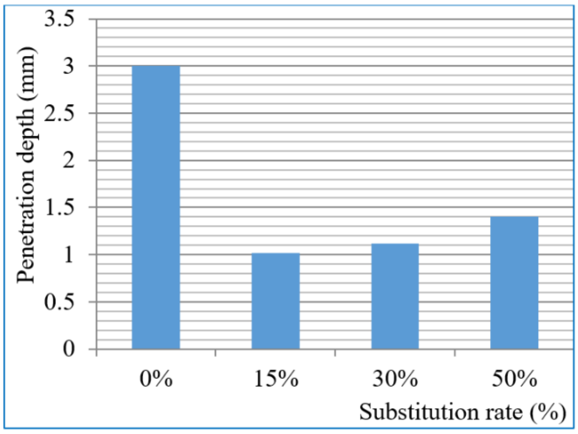


Figure 10. Variation of chloride penetration depth as a function of the substitution rate

5. MODELING OF THE MECHANICAL RESPONSE

The statistical analysis was conducted using different modeling approaches depending on the nature of each investigated durability response.

For responses governed by a single independent variable, namely the recycled tile waste sand content, a one-factor linear regression model was applied. This approach was used for the analysis of water absorption by immersion and chloride penetration depth, where the variation of the response is mainly dependent on the substitution rate of recycled sand. The model can be expressed as Eq. (4).

$$Y = B_0 + B_1 X \quad (4)$$

where, *Y* is the response variable, *X* is the recycled sand content, B_0 is the intercept, and B_1 is the regression coefficient.

For the remaining durability properties, including capillary water absorption, mass loss in acidic solutions (HCl, H_2SO_4, CH_3COOH), and mass gain in NaCl solution, a two-factor full factorial design was adopted. In this study, recycled tile waste sand content (X_1) was considered as the first factor with four substitution rates (0%, 15%, 30%, and 50%), while exposure time (X_2) was used as the second factor with three levels (7, 28, and 90 days). This design enabled the evaluation of both the main effects and the interaction effects of these parameters on the studied responses. The corresponding first-order linear regression model with interaction is given by Eq. (5).

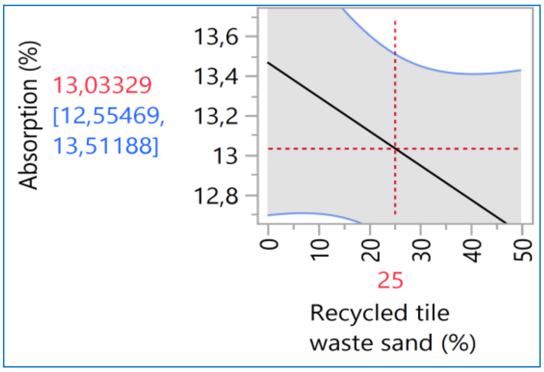
$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_{12} X_1 X_2 \quad (5)$$

where, X_1 represents the recycled sand content, X_2 represents the exposure time, and B_{12} is the interaction coefficient accounting for the combined effect of both factors.

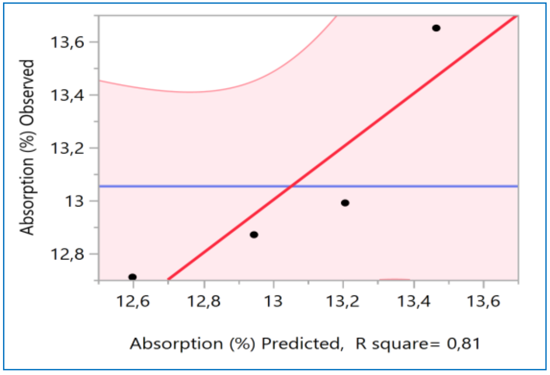
This combined approach allows a more appropriate interpretation of each response depending on its governing variables, while avoiding over-parameterization of the statistical models.

5.1 Water absorption by immersion

Figure 11 illustrates the water absorption results, where Figure 11(a) presents the main effect of the examined variable, and Figure 11(b) shows the correlation between the experimental measurements and the model predictions. The agreement between the observed and predicted values indicates a generally consistent predictive behavior of the proposed model in describing water absorption.



(a) Main effect plots of water absorption



(b) Evolution of correlation between experimental and predicted values of water absorption

Figure 11. Analysis of water absorption through main effect plots and correlation between experimental and predicted values

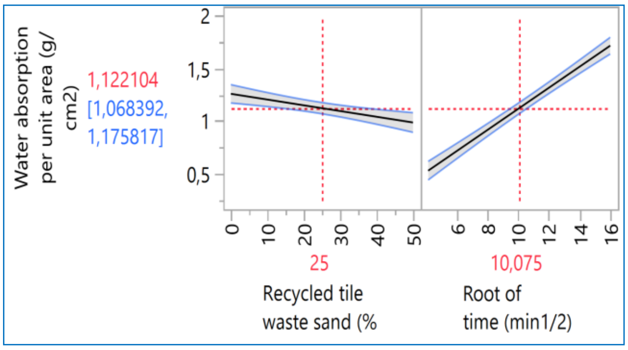
Table 3. Regression coefficients and significance test of the recycled tile waste sand factor for water absorption

Term	Estimate	Standard Error	t Ratio	Prob. > |t|
Recycled tile waste sand (%) (0-50)	-0.434247	0.149986	-2.90	0.1015

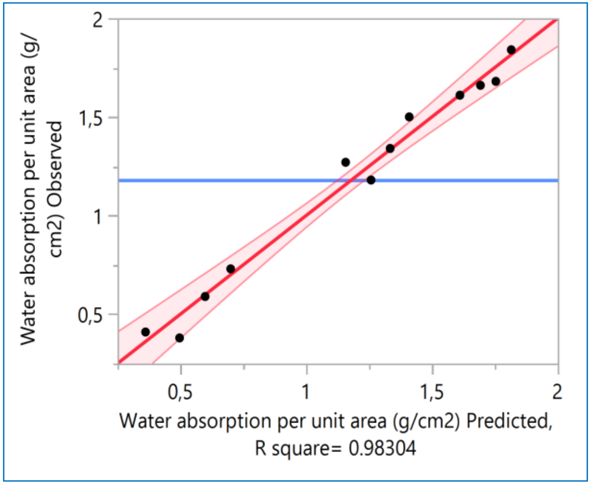
The results summarized in Table 3 indicate that the incorporation of recycled tile waste sand, within the range of 0–50%, produces a negative estimated coefficient (−0.434). This finding suggests that higher substitution rates of recycled tile waste sand are associated with lower water absorption values. This improvement can be explained by the refinement of the pore structure and the enhanced packing density induced by the fine recycled particles [28]. Although the t-value (−2.90) reflects a noticeable contribution of recycled tile waste sand to water absorption, the associated probability value (Prob. > |t| = 0.1015) exceeds the 5% significance threshold. Therefore, the effect is not statistically significant within the studied range (0–50%). Nevertheless, the consistent downward trend remains of practical interest, indicating that recycled tile waste sand can contribute positively to improving the durability performance of mortar by reducing its susceptibility to water penetration [29].

5.2 Water absorption by capillarity

Figure 12(a) shows that increasing the recycled sand content leads to a noticeable reduction in water absorption, while the increase in exposure time results in higher absorption values. This trend is confirmed by the results in Table 4, where recycled tile waste sand shows a negative effect on water absorption, corresponding to a reduction of approximately 12% in water absorption. Conversely, the root of time has a significant positive influence, leading to an increase of about 53% in water absorption. The interaction between recycled sand and exposure time is not statistically significant, indicating that the beneficial effect of recycled sand remains stable regardless of time. Furthermore, Figure 12(b) shows a general agreement between experimental and predicted values, suggesting a consistent predictive behavior of the developed model.



(a) Main effect plots of water absorption per unit area



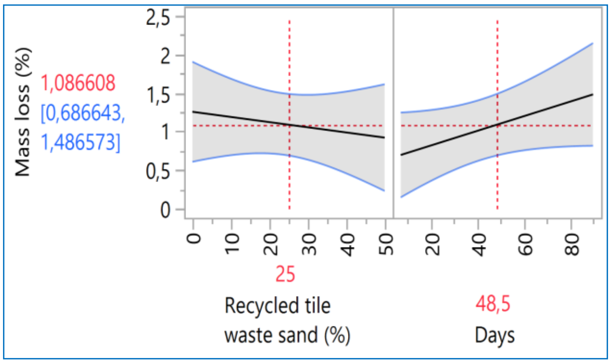
(b) Evolution of correlation between experimental and predicted values of water absorption per unit area

Figure 12. Analysis of water absorption per unit area through main effect plots and correlation between experimental and predicted values

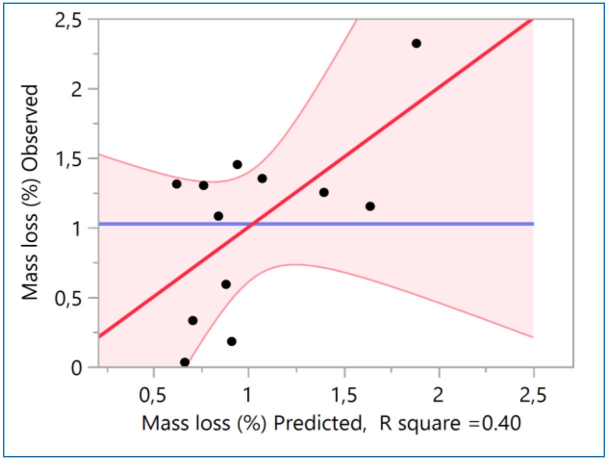
5.3 Mass loss stored in HCl solution

Figure 13(a) depicts the main effects of the studied parameters. It can be observed that the incorporation of recycled tile waste sand exhibits a slight negative effect on mass loss, indicating a marginal improvement in resistance to acid attack. However, this effect remains limited, suggesting that the substitution rate used does not significantly alter the degradation behavior. In contrast, exposure duration shows a clear increasing trend, confirming that prolonged immersion in the acidic medium intensifies mass loss due to continuous dissolution of cementitious phases [30, 31].

Figure 13(b) shows an acceptable agreement between the experimental and predicted values for mass loss.



(a) Main effect plots of mass loss stored in HCl solution



(b) Evolution of correlation between experimental and predicted values of mass loss stored in HCl solution

Figure 13. Analysis of mass loss of different mortars stored in HCl solution through main effect plots and correlation between experimental and predicted values

Table 4. Regression coefficients and significance test of the recycled tile waste sand factor for water absorption by capillarity

Term	Estimate	Standard Error	t Ratio	Prob. > |t|
Constant	1.1221043	0.023292	48.17	<0.0001*
Recycled tile waste sand (%) (0-50)	-0.135551	0.031407	-4.32	0.0026*
Root of time (min$^{1/2}$)	0.5911493	0.028011	21.10	<0.0001*
Recycled tile waste sand (%)*Root of time (min$^{1/2}$)	0.03358	0.037769	0.89	0.3999

Note: * Interaction between recycled tile waste sand and root of time

The statistical significance of these observations is summarized in Table 5. The constant term is highly significant (p = 0.0002), indicating the strong baseline contribution of the model. The recycled tile waste sand content shows a non-significant effect (p = 0.4941), confirming that its isolated influence on mass loss is statistically negligible within the investigated range. Conversely, the exposure duration presents a near-significant effect (p = 0.0858), highlighting its dominant role in controlling the deterioration process.

Table 5. Regression coefficients and significance analysis of factors affecting mass loss in HCl solution

Term	Estimate	Standard Error	t Ratio	Prob. > |t|
Constant	1.086608	0.173445	6.26	0.0002*
Recycled tile waste sand (%) (0-50)	-0.16757	0.233873	-0.72	0.4941
Days (7- 90)	0.3928744	0.200544	1.96	0.0858
Recycled tile waste sand (%)*Days	-0.23843	0.270413	-0.88	0.4036

Note: * Interaction between recycled tile waste sand and days

Moreover, the interaction between recycled tile waste sand content and exposure duration is also non-significant (p = 0.4036), suggesting that the combined effect of these parameters does not amplify mass loss beyond their individual contributions. This indicates that the degradation mechanism is primarily governed by the aggressive environment rather than by the presence of recycled material [32].

Overall, these findings demonstrate that while recycled tile waste sand can be incorporated without adversely affecting durability, the exposure time in acidic media remains the principal factor influencing mass loss. This outcome supports the feasibility of using recycled tile waste sand in mortar applications subjected to aggressive environments, provided that durability requirements are carefully considered.

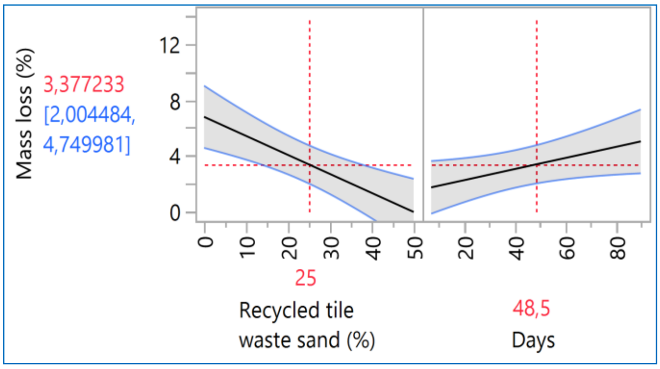
5.4 Mass loss stored in H_2SO_4 solution

As shown in Figure 14(a), the incorporation of recycled tile waste sand has a pronounced influence on mass loss. The negative trend associated with increasing recycled sand content indicates a significant reduction in mass loss, reflecting an improvement in the resistance of mortar to sulfuric acid attack. This behavior suggests that the presence of recycled tile waste sand contributes to limiting the degradation of the cementitious matrix under highly aggressive conditions [33]. In parallel, exposure duration exhibits a positive effect, where prolonged immersion leads to increased mass loss, confirming the progressive deterioration of mortar over time.

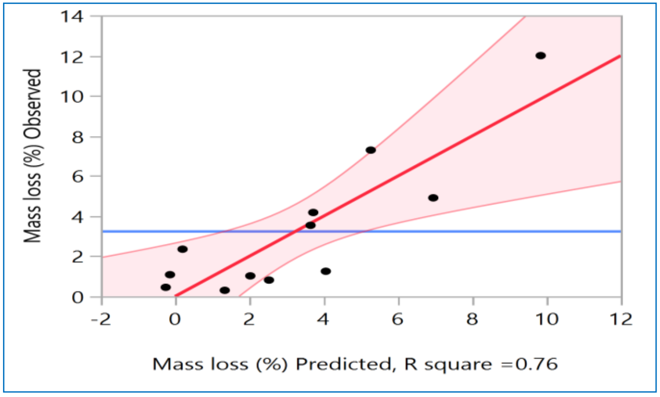
Figure 14(b) demonstrates the relationship between experimental and predicted mass loss values. The close alignment between both sets of data highlights the high predictive accuracy of the developed model, confirming its suitability for describing the degradation behavior of mortar exposed to sulfuric acid [34].

The statistical significance of these effects is confirmed by the results presented in Table 6. The constant term is highly significant (p = 0.0005), indicating the robustness of the regression model. The recycled tile waste sand content shows a statistically significant negative effect on mass loss (p = 0.0028), emphasizing its beneficial role in enhancing acid resistance. Similarly, the exposure duration is statistically significant (p = 0.0440), demonstrating its dominant contribution to mortar degradation.

In contrast, the interaction between recycled tile waste sand content and exposure duration is not statistically significant (p = 0.1652), indicating that their combined effect does not intensify mass loss beyond their individual influences. Overall, these findings confirm that sulfuric acid exposure strongly affects mortar durability, while the use of recycled tile waste sand significantly mitigates mass loss, supporting its application in aggressive environments [35].



(a) Main effect plots of mass loss stored in H_2SO_4 solution



(b) Evolution of correlation between experimental and predicted values of mass loss stored in H_2SO_4 solution

Figure 14. Analysis of mass loss of different mortars stored in H_2SO_4 solution through main effect plots and correlation between experimental and predicted values

Table 6. Regression coefficients and significance analysis of factors affecting mass loss in H_2SO_4 solution

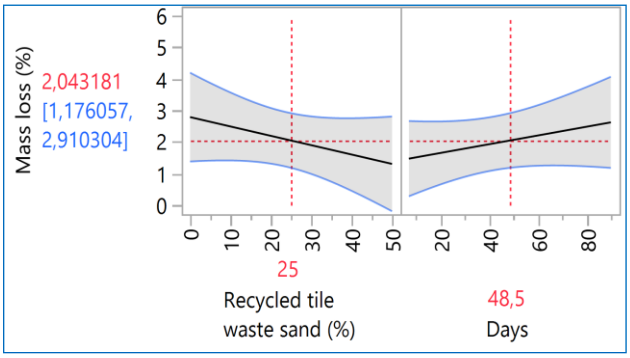
Term	Estimate	Standard Error	t Ratio	Prob. > |t|
Constant	3.3772326	0.595293	5.67	0.0005*
Recycled tile waste sand (%) (0-50)	-3.402481	0.802693	-4.24	0.0028*
Days (7-90)	1.6439324	0.688302	2.39	0.0440*
Recycled tile waste sand (%)*Days	-1.417348	0.928106	-1.53	0.1652

5.5 Mass loss stored in CH_3COOH solution

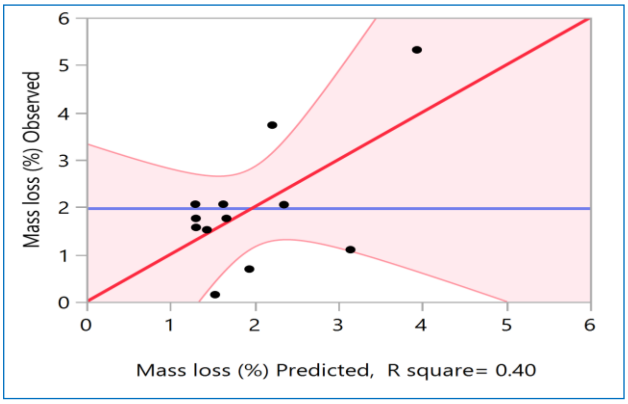
The behavior of concrete incorporating recycled tile waste sand under acetic acid exposure is analyzed using Figure 15 and Table 7, which describe the variation in mass loss as a function of material composition and immersion time.

The trends observed in Figure 15(a) indicate that the effect of recycled tile waste sand on mass loss is relatively weak.

Although a slight decreasing tendency can be identified with increasing recycled sand content, the overall variation remains limited. This suggests that, in an acetic acid environment, the replacement of natural sand with recycled tile waste sand does not substantially alter the degradation kinetics of mortar [30].



(a) Main effect plots of mass loss stored in CH_3COOH solution



(b) Evolution of correlation between experimental and predicted values of mass loss stored in CH_3COOH solution

Figure 15. Analysis of mass loss of different mortars stored in CH_3COOH solution through main effect plots and correlation between experimental and predicted values

Table 7. Regression coefficients and significance analysis of factors affecting mass loss in CH_3COOH solustion

Term	Estimate	Standard Error	t Ratio	Prob. > |t|
Constant	2.0431805	0.376029	5.43	0.0006*
Recycled tile waste sand (%) (0-50)	-0.740893	0.507037	-1.46	0.1821
Days (7- 90)	0.5746829	0.434779	1.32	0.2228
Recycled tile waste sand (%)*Days	-0.578815	0.586256	-0.99	0.3524

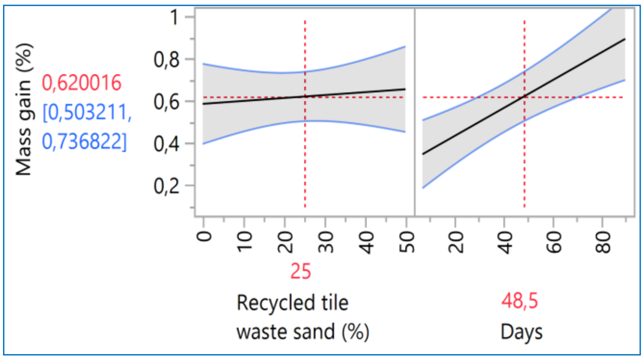
The comparison between experimental measurements and model predictions shown in Figure 15(b) reveals a satisfactory level of agreement. This consistency demonstrates that the proposed regression model is capable of adequately reproducing the observed mass loss behavior, despite the modest sensitivity of the system to the studied parameters.

In summary, the deterioration of mortar in acetic acid solution is governed by a mild and gradual process. The incorporation of recycled tile waste sand neither significantly enhances nor compromises durability, supporting its use in concrete exposed to weak acidic environments without adverse effects on performance.

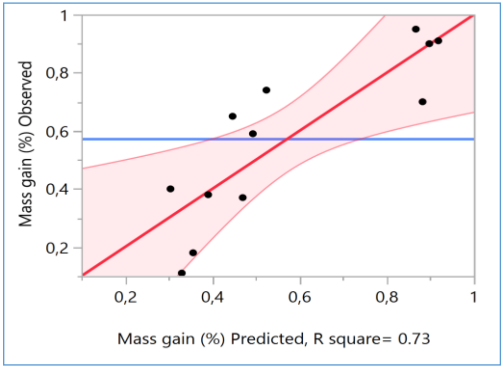
Further insight is provided by the statistical significance results in Table 7, which confirm that the regression model is statistically reliable, as evidenced by the significant constant term ($p = 0.0006$). However, neither the recycled tile waste sand content nor the exposure duration exhibits a statistically significant effect on mass loss ($p > 0.05$). Additionally, the interaction between these two factors remains non-significant, indicating the absence of synergistic effects in the degradation mechanism [31].

5.6 Mass gain sorted in NaCl solution

As shown in Figure 16(a), mass gain increases markedly with exposure duration, indicating progressive chloride ingress and accumulation within the pore structure of the concrete. According to the model estimation, increasing the exposure period from 7 to 90 days results in an approximate 44% increase in mass gain relative to the initial condition. This significant rise is attributed to salt absorption and crystallization processes occurring inside the cementitious matrix [32].



(a) Main effect plots of mass gain



(b) Evolution of correlation between experimental and predicted values of mass gain

Figure 16. Analysis of mass gain of different mortars stored in NaCL solution through main effect plots and correlation between experimental and predicted values

In contrast, the incorporation of recycled tile waste sand shows a minimal effect on mass gain. The observed variation corresponds to a limited increase of approximately 5–6%, which remains statistically insignificant. This indicates that replacing natural sand with recycled tile waste sand does not substantially alter the chloride uptake behavior of mortar.

The correlation between experimental and predicted values presented in Figure 16(b) demonstrates a strong agreement, confirming the accuracy and robustness of the developed predictive model.

The statistical significance results presented in Table 8 further corroborate these findings. The intercept term is highly significant ($p < 0.0001$), confirming the robustness of the statistical model. Exposure duration exhibits a statistically significant effect on mass gain ($p = 0.0016$), highlighting its predominant influence on the absorption process. In contrast, the recycled tile waste sand content ($p = 0.6272$) and its interaction with exposure duration ($p = 0.9148$) do not show statistical significance, indicating their minimal contribution to mass gain [33].

Table 8. Regression coefficients and significance analysis of factors affecting mass loss in NaCl solution

Term	Estimate	Standard Error	t Ratio	Prob. > |t|
Constant	0.6200163	0.050653	12.24	<0.0001*
Recycled tile waste sand (%) (0-50)	0.0344843	0.0683	0.50	0.6272
Days (7-90)	0.2726062	0.058567	4.65	0.0016*
Recycled tile waste sand (%) * Days	-0.008724	0.078971	-0.11	0.9148

In summary, mass gain in a NaCl solution is mainly controlled by exposure time, whereas the incorporation of recycled tile waste sand does not negatively influence chloride uptake. These results demonstrate the suitability of recycled tile waste sand for use in mortar structures subjected to saline environments.

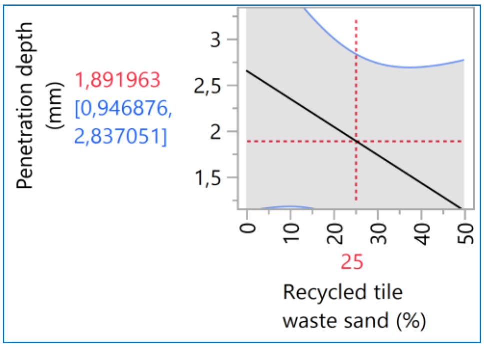
5.7 Chloride penetration

The penetration depth results are presented in Figure 17 and summarized statistically in Table 9. A linear regression model was employed to assess the influence of recycled tile waste sand content on penetration depth. As shown in Figure 17, the predicted values exhibit a reasonable agreement with the experimental data, indicating an acceptable model fit.

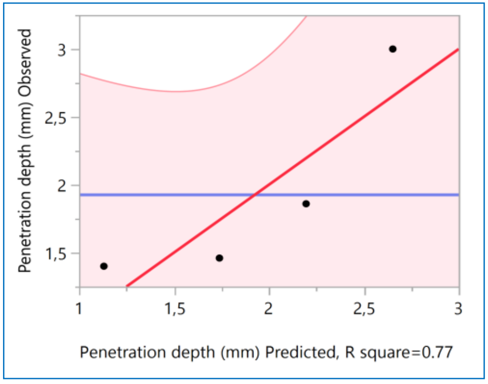
The statistical parameters reported in Table 9 show that the model explains a significant portion of the variability in penetration depth, with a coefficient of determination (R^2) of 0.77. This suggests that approximately 77% of the variation in penetration depth can be attributed to the recycled tile waste sand content.

The regression coefficient associated with recycled tile waste sand content is negative (−0.76), as reported in Table 9, indicating an inverse relationship between recycled sand content and penetration depth. This trend, also illustrated in Figure 17, suggests that increasing the proportion of recycled tile waste sand tends to reduce penetration depth. Such behavior may be linked to improved compactness of the mortar matrix and enhanced resistance to penetration. Nevertheless, given the statistical insignificance [34].

Residual analyses illustrated in Figure 17, including studentized and externally studentized residuals with Bonferroni limits, reveal no extreme outliers, confirming that the assumptions of linear regression are reasonably satisfied. The root mean square error (RMSE) of 0.44 mm further indicates a moderate dispersion between observed and predicted values, while the mean penetration depth is approximately 1.93 mm.



(a) Main effect plots of chloride penetration depth



(b) Evolution of correlation between experimental and predicted values of chloride penetration depth

Figure 17. Analysis of chloride penetration depth as a function of the substitution rate through main effect plots and correlation between experimental and predicted values

Table 9. Regression coefficients and significance analysis of factors affecting the variation of chloride penetration depth

Term	Estimate	Standard Error	t Ratio	Prob. > |t|
Recycled tile waste sand (%) (0-50)	-0.760731	0.296179	-2.57	0.1240

Overall, the combined interpretation of Figure 17 and Table 9 suggests a potentially beneficial influence of recycled tile waste sand in reducing penetration depth.

6. CONCLUSIONS

The present study investigated the incorporation of recycled tile waste sand as a partial replacement for natural sand in Diss fiber-reinforced mortar through experimental testing and statistical modeling, with a particular focus on durability performance.

The results indicate that the use of recycled tile waste sand reduces water absorption, both by immersion and capillarity, reflecting an improvement in the compactness of the cementitious matrix. In addition, mortars incorporating recycled sand exhibit enhanced resistance to aggressive environments compared to conventional mortar.

An optimal substitution rate of 15% was identified for most durability properties, particularly in acidic (HCl, CH_3COOH) and saline (NaCl) environments. However, under H_2SO_4 exposure, higher substitution rates demonstrated improved resistance, highlighting the influence of the type of aggressive medium.

Furthermore, the incorporation of recycled sand contributes to reducing chloride ion penetration, indicating improved durability against ionic ingress.

Statistical analysis revealed a general decreasing trend in water absorption with increasing recycled sand content, with acceptable agreement between experimental and predicted values. While the influence of recycled sand on mass loss in HCl and CH_3COOH solutions was statistically non-significant, a significant reduction was observed under H_2SO_4 exposure, confirming enhanced resistance to severe acid attack.

The regression analysis also indicated an inverse relationship between recycled sand content and chloride penetration depth. Although this effect was not statistically significant, the observed trend suggests a beneficial influence on durability.

Overall, the incorporation of recycled tile waste sand represents a sustainable and effective approach to improving mortar durability. Such materials can be recommended for use in filling applications, masonry, and the rehabilitation of existing structures, particularly in moderately aggressive and marine environments.

ACKNOWLEDGMENT

I would like to thank the LMGHU laboratory team for their dedicated efforts and continuous commitment to this research. Their scientific support, valuable guidance, and collaboration greatly contributed to the successful completion of this work.

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