Predicting the durability of stabilized soil blocks using non-destructive testing

Zohreh Ghafouri Fard[1], Maryam Mokhtari[1][1], Mohammad Mehdi Khabiri[1] , Seyed Mehrdad Jalilian [2]

[1] Department of Civil Engineering, Faculty of Engineering, Yazd University, Iran
[2] Department of Polymer, Faculty of Polymer, Iran Polymer and Petrochemical Research Institute, Tehran, Iran

Abstract:

The use of non-destructive tests for predicting the durability of stabilized earthen blocks, in addition to environmental benefits, enhances the reliability, safety, and cost-effectiveness of structures. The durability of earthen blocks, defined as their ability to withstand environmental factors such as moisture, temperature variations, and erosion, plays a critical role in the lifespan of structures, reducing maintenance costs, and preserving the environment. This study aims to predict the durability properties of earthen blocks stabilized with synthetic copolymers and to develop predictive models based on a combination of destructive and non-destructive tests. The destructive tests included freeze–thaw cycles, wet–dry cycles, and erosion tests, while the non-destructive tests comprised water absorption, ultrasonic testing, contact angle measurement, and image processing. The results were modeled using Response Surface Methodology (RSM) in Design Expert software. The findings demonstrated that non-destructive tests effectively reflect the changes in blocks under various conditions, and their appropriate combination enables accurate prediction of earthen block performance. Multivariate models described the degradation trends, environmental cycle sensitivity, and the effects of polymer content and construction quality better than univariate models. Additionally, some non-destructive tests played a key role in durability prediction and can be selected as primary indicators for rapid assessment.

The results indicate that combining non-destructive testing and modeling is an effective alternative to destructive testing, contributing to significant reductions in cost, time, and resources in sustainable earthen block projects.

[1] Corresponding Author: Email: mokhtar@yazd.ac.ir

Keywords:

Response surface methodology, Stabilized soil block, Synthetic polymer, Non-destructive tests, Block durability properties

1. Introduction

For thousands of years, soil has been used to produce blocks for the construction of residential structures [1]. Today, the use of earthen materials can be a significant step towards sustainable development and addressing the environmental issues of civil engineering projects, as well as enhancing their compatibility with the environment [2], [3]. Earth blocks are among the environmentally friendly earthen materials [4], [5] that have particular importance in the construction industry owing to their environmental, economic, and technical advantages [6].These blocks are produced using locally available soil and, when necessary, stabilizers, contributing to reducing the transportation costs of materials, decreasing construction waste, and improving energy efficiency [7], [8].

Concerns about the vulnerability of such materials in the face of various environmental hazards have led to numerous studies on their durability properties. For instance, Elahi et al. noted that the use of fly ash in the production of compressed stabilized earth blocks can be an effective way of enhancing sustainability. On this basis, they investigated the resistance of cement- and fly ash-stabilized earth blocks to wet-dry cycles. They found that increasing the fly ash content improved the durability and reduced the weight loss of the blocks due to wet-dry cycling [9]. Nshimiyimana et al. also evaluated the durability of compressed earth blocks and concluded that these blocks exhibit acceptable resistance to freeze-thaw cycles and erosion, while simultaneously serving as sustainable, environmentally friendly materials [10]. Furthermore, Bruno et al. assessed the compressive strength of three types of earth blocks, including medium-density earth blocks, high-density earth blocks, and fiber-stabilized earth blocks, after freeze-thaw cycles as a parameter for comparing and investigating the durability of earth blocks [11]. The results of their study indicate that high-density earth blocks and fiber-stabilized earth blocks demonstrate superior performance against freeze-thaw cycles.

In 2023, Paul et al. investigated the durability of compressed earth blocks stabilized with rice husk ash and cement. For this purpose, the blocks were prepared and examined with different cement contents (4%, 6%, and 8% by weight of dry soil) and five different amounts of rice husk ash (0%, 5%, 10%, 15%, and 20% by weight of dry soil). The results indicated that the earth blocks stabilized with a combination of lower cement content and 5-10% rice husk ash had better durability than the samples produced with higher cement content. This demonstrates the suitability of rice husk ash as a partial replacement for cement [12]. Furthermore, noting that earth blocks have long been recognized as an environmentally friendly and suitable alternative to the traditional building blocks that harm the environment, Aninda and Islam investigated the performance of blocks stabilized with cement and plastic waste[13]. With a focus on durability, the research showed that replacing cement with plastic waste as a stabilizer would significantly improve the durability of the blocks . Additionally, Latha et al. explored the potential of municipal solid waste incineration bottom ash as a partial replacement for ordinary Portland cement as a stabilizer in the production of compressed stabilized earth blocks. It was shown that the blocks manufactured with 20% incineration bottom ash content and 10% cement were able to meet the required strength and durability criteria [14].

Noting that some earthen structures in cold regions are exposed to severe climatic changes and, consequently, to frequent freeze-thaw cycles due to significant temperature fluctuations, Liu et al. investigated the freeze-thaw cycles of these materials. They found that freeze-thaw cycles can cause severe damage to compressed earth materials and reduce the structure durability. They also indicated that, with an increasing number of freeze-thaw cycles, the Young's modulus increased in the frozen state of the material, while the opposite trend was observed in the thawed state [15]. In another study in 2024, Paul et al. examined the addition of arcca fiber as a reinforcing agent to cement-stabilized compressed earth blocks. As they found, the fiber addition promoted the microstructural integrity, enhanced the bonding and stability between the soil particles, and led to improved durability and resistance against various environmental conditions [16]. In the same field, Pederson et al. studied the feasibility of using buffalo grass as a reinforcing fiber in stabilized earth blocks. It was observed that adding this fiber not only enhanced the mechanical properties of the block but also improved its resistance to wet-dry cycles[17]. In 2025, Mohammed et al. conducted a study on the durability of earth blocks stabilized with environmentally compatible materials such as palm oil fuel ash, palm oil clinker, ground palm oil clinker, and stone dust. The evaluation was performed with two laboratory methods and in one year of exposure to real weathering conditions. The results showed that the weight loss of the blocks under laboratory wet-dry cycles ranged from 1.51% to 0.87%, while their weight loss under real weather conditions varied from 1.27% to 0.54%. This indicates that those blocks performed better than conventional traditional ones, as the weight loss in both scenarios was significantly lower [18]. In a study conducted in 2025, earth blocks incorporating two agro-industrial by-products, wheat straw (WS) and cork granules (CGs), were investigated. Based on the results, the lowest addition rate of 5% WS provided the best balance between mechanical performance and durability. In contrast, the addition of CGs had to be limited to 3-5% so as to prevent a significant reduction in strength and durability [19].

As mentioned, numerous studies have been conducted on the durability of earth blocks stabilized with various types of stabilizers. Meanwhile, polymers have gained a special status in civil engineering and construction due to their unique properties; consequently, researchers have focused their studies on the stabilization of earth blocks with polymers. For instance, in 2019, melted plastic waste was used as a type of recycled polymer to stabilize earth blocks, and it was indicated that blocks made with this polymer could be suitable for paving in non-motorized, light-traffic pathways [20]. In a similar study, Tempa et al. investigated the stabilization of earth blocks using melted plastic waste as a recycled polymer and cement. The results showed that compressive strength would increase with the addition of plastic. However, when the block was exposed to very high temperatures, its strength decreased by 17.31%. Additionally, the plastic pavement block had a low water absorption potential, which increased its durability [21]. Regarding the use of recycled polymers, one may also refer to a study by Nanorm et al. In that study, plastic waste was melted and then mixed with sand with particle sizes smaller than 2 mm in the sand-to-plastic ratios of 1:1, 1:3, and 3:1. The results indicated the suitable mechanical performance and durability of these blocks for use as pavement in pathways [22]. In a 2023 study, Iftikhar et al. found that recycling plastic waste as a recycled polymer to replace cement can be an effective solution for minimizing waste and eliminating cement, producing an environmentally friendly and durable block [23]. Furthermore, the research conducted by Karisma demonstrated that earth blocks stabilized with recycled polymer exhibit satisfactory performance in terms of compressive strength and water absorption. Since no cement is used in their production, they are also environmentally friendly[24].

Regarding the use of polymers for soil stabilization, one may refer to the study by Kocak and Grant. They investigated building materials stabilized with a synthetic emulsion polymer and found that soil stabilization with polymer improves strength and durability, thereby providing the necessary properties for its use in sustainable earth construction [25]. Similarly, Ghafouri Fard et al. investigated the durability of earth blocks stabilized with A50 acrylic emulsion copolymer, an environmentally friendly polymer. For this purpose, they prepared earth block samples with different polymer percentages (5% to 20%) and subjected them to tests for compressive strength, water absorption, capillary absorption, wet-dry cycles, and freeze-thaw cycles. It was indicated that the use of A50 copolymer can effectively enhance the durability of earth blocks against environmental factors [26].

Despite the numerous studies on the durability of stabilized earth blocks and polymer-stabilized earth blocks, limited research has been conducted on predicting the properties of earth blocks using mathematical models. Among the few studies, the one by Raavi and Tripura can be mentioned. They conducted a series of statistical analyses to predict the compressive and tensile strength in relation to the percentage and length of coconut fibers, as well as the cement content. The equations derived from regression analysis showed a strong correlation between the actual and predicted values, which can be used for the accurate prediction of rammed earth strength [27]. In another study , machine learning techniques were used to predict the compressive strength of stabilized earth blocks based on cement content, electrical resistivity, and ultrasonic pulse velocity. By providing reliable predictive models for evaluating the mechanical properties of earth blocks, the research results significantly assist engineers in the field of construction [28]. Moreover, Turco et al. investigated the use of artificial neural networks (ANNs) to predict the compressive and tensile strength of natural fiber-reinforced compressed earth blocks. Based on the results of the analyses, the proposed relationships accurately predicted the performance of the studied blocks [29].

The literature is rich in studies on stabilized soil blocks, but there seems to be just a little research about the durability properties of soil blocks stabilized with environmentally friendly synthetic polymers. Also, since fabricating specimens and conducting experiments to evaluate the performance of these blocks is costly and time-consuming, the present research aims to predict the durability performance of soil blocks stabilized with two types of environmentally friendly synthetic emulsion copolymers using non-destructive tests through the response surface methodology. In fact, despite numerous studies on predicting the properties of earthen blocks, a comprehensive framework for forecasting the durability of copolymer-stabilized, environmentally friendly earthen blocks based on non-destructive indicators has yet to be established. Although previous research has examined durability behavior and the performance of certain polymer additives, the quantitative and multivariate relationships between non-destructive test results and key destructive durability indices—such as wet–dry cycles, freeze–thaw cycles, and erosion—have not been systematically analyzed. This gap limits the ability to perform rapid, economical, and reliable durability assessments of earthen blocks during design and quality control stages. To address this shortcoming, the present study focuses on two types of synthetic copolymers—styrene–acrylate and styrene–butadiene—and evaluates their effects on the microstructure, water absorption, and environmental stability of earthen blocks. Subsequently, using the Response Surface Methodology (RSM), multivariate predictive models are developed to link non-destructive tests (water absorption, ultrasonic wave velocity, droplet contact angle, and image-analysis-derived indices) to the results of destructive durability tests.

It is worth noting that the soil stabilization mechanism provided by synthetic copolymers can be described at three levels: microstructural, physical, and chemical. After the copolymer is mixed with the soil, the polymer chains, in the presence of water, effectively penetrate into the voids and interparticle spaces. During the drying stage, they form a three-dimensional polymer network that encapsulates both fine and coarse particles and creates interparticle bonding bridges. By reducing the void ratio, this network increases effective compaction and decreases permeability. At the chemical level, the active functional groups in the copolymer (such as carboxyl, hydroxyl, or amine groups) interact with the surfaces of clay minerals through hydrogen bonding, van der Waals forces, or quasi-covalent bonds, forming a stabilizing layer around the particles. This layer prevents clay swelling and moisture-induced particle separation, improving the dimensional stability of the block during wet–dry cycles. Furthermore, the formation of a continuous polymer film on particle surfaces and within void spaces enhances water repellency and reduces the absorption of free water—factors that directly contribute to mitigating freeze–thaw damage and erosion. Overall, these processes increase mechanical strength, reduce permeability, and improve the block's performance under moisture and temperature variations, thereby significantly enhancing the material's durability[30].

2. Research method

2-1- Materials and sample preparation

To produce soil blocks stabilized with an emulsion copolymer, the sand used was mixed with styrene-acrylate (A) and styrene-butadiene (B) according to the specifications provided in Table 1. This was done through mixing varying percentages of the materials as detailed in Table 2 (Figure 1-a). The mixtures were then poured into the corresponding molds and dried at ambient temperature (Figure 1-b). It should be noted that the rationale for using these two synthetic polymers is that both are in an emulsion form, which allows them to mix easily with soil. Moreover, and most importantly, the employed copolymers are environmentally friendly, leading to the production of stabilized soil blocks that are compatible with the environment. These blocks can serve as a suitable alternative to traditional stabilizing materials such as cement and lime, whose production causes environmental damage and pollution..

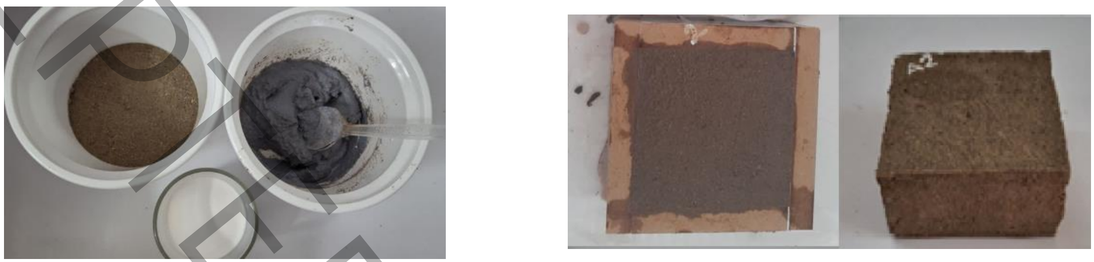
Table 1. Consumable material specifications

Copolymer			Wind-blown sand soil	
Styrene-Butadiene	Styrene-Acrylate	property	Values	property
$C_6H_5CH{=}CH_2$ + ($CH_2{=}CH\text{-}CH{=}CH_2$)	$C_6H_5CH{=}CH_2$ + ($CH_2{=}CHCOOCH_3$)	monomers	Light brown	Color
-50−20	20−40	Glass transition temperature (°C)	12	Optimum humidity percentage
50000−300000	100000−300000	Molecular weight (g/mol)	1.73	Maximum dry density (gr/cm^3)
٦–٧	6−7	PH	0	Plasticity index
1.1−1.3	١,١–١,٣	Density(g/cm2)	4	Sand value
Depends on concentration	Depends on concentration	Solids percentage	2.67	Specific density

Table 2. Different percentages of soil block stabilization

Sample code		Amount of pure polymer by weight percentage
A0	B0	2.5
A1	B1	5
A2	B2	10
A3	B3	15
A4	B4	20
A5	B5	25
A6	B6	30

It should be noted that the percentage range of 2.5 to 30 for the pure polymer content was selected based on technical and empirical considerations. Polymer contents below 2.5% result in earthen blocks with insufficient stability, leading to damage during construction and use stages. Conversely, polymer contents above 30% significantly increase the polymer's concentration and viscosity, making the block manufacturing process very difficult and costly.



A B

Figure 1. Stages of constructing stabilized soil blocks

2-2- Experiments

t is recommonded to use Endnote to site your In this study, a number of specimens were first prepared and subjected to destructive durability tests including freeze-thaw cycles for paving blocks, freeze-thaw cycles for non-loadbearing blocks, abrasion resistance, and wet-dry cycles in accordance with standards BS EN 1338 and EN 771-3. Then, a second group of specimens was prepared and put to non-destructive testing, which are elaborated upon in this section.

2.2.1. Water absorption by immersion

Water absorption through the immersion of soil blocks is a common method of measuring the water absorption capacity and water penetration rate in compacted earthen materials or soil blocks. Therefore, the objective of this test is to determine the amount of the water absorbed by the soil block over a specific period and to evaluate the resistance of soil blocks to water erosion or disintegration due to moisture absorption.

According to the ASTM C140 standard, the specimens are oven-dried to remove their initial moisture content, and the dry weight of the blocks is measured. They are then fully immersed in water for 24 hours. The water absorption percentage is subsequently calculated by determining the ratio of the weight change to the final weight of the specimen (Figure 2-a).

2.2.2. Water absorption by capillarity

Capillarity occurs when adhesive forces (between water and soil particles) and cohesive forces (between water molecules) cause water to move through the fine pores of the soil. Capillary action is one of the most important mechanisms for moisture transport within earthen materials. This phenomenon is particularly significant in building materials such as earthen bricks, compressed earth blocks, and earthen floorings. Therefore, in this study, water absorption by capillarity was investigated in accordance with the standard XP P 13-901, as illustrated in Figure 2-b.

2.2.3. Ultrasonic testing

Ultrasonic testing is a non-destructive method of evaluating the quality of materials, detecting cracks and porosity, and measuring the velocity of sound waves in specimens. This method is widely used in geotechnical, civil, and construction materials engineering. Therefore, in this research, the ultrasonic test was conducted in accordance with the ASTM C597 standard, an image of which is presented in Figure 2-c.

2.2.4. Contact Angle Test

The contact angle measurement is a crucial method of investigating the surface properties of materials, particularly their hydrophobicity or hydrophilicity. This test is performed by measuring the angle between the surface of the material and a liquid droplet (typically water). Currently, this is extensively applied in studying the properties of civil engineering materials [31]. As mentioned, this test can be used to examine the hydrophobic and hydrophilic properties of materials. Accordingly, a surface is considered super-hydrophilic if the contact angle is less than 10°, hydrophilic if between 10° and 90°, hydrophobic if between 90° and 150°, and super-hydrophobic if greater than 150°. The sample images from this test are shown in Figure 2-d.

2.2.5. Analysis of surface porosity via image processing

Image processing is used in civil engineering as a non-destructive, precise, and low-cost method of analyzing surface and internal structure, as well as determining particle distribution and porosity. The general procedure involves image acquisition and subsequent processing using appropriate software. In this study, images were taken using a mobile phone camera under consistent lighting and angle conditions. The image analysis was performed with the MATLAB software. It is noteworthy that MATLAB is one of the most powerful software packages for processing images, providing specialized tools for analyzing material images, detecting cracks, and measuring porosity. For this purpose, the images of the blocks were taken under uniform conditions, and the surface void ratio and porosity were determined using image processing. In this research, surface porosity was used as a representative measure of the total sample porosity.

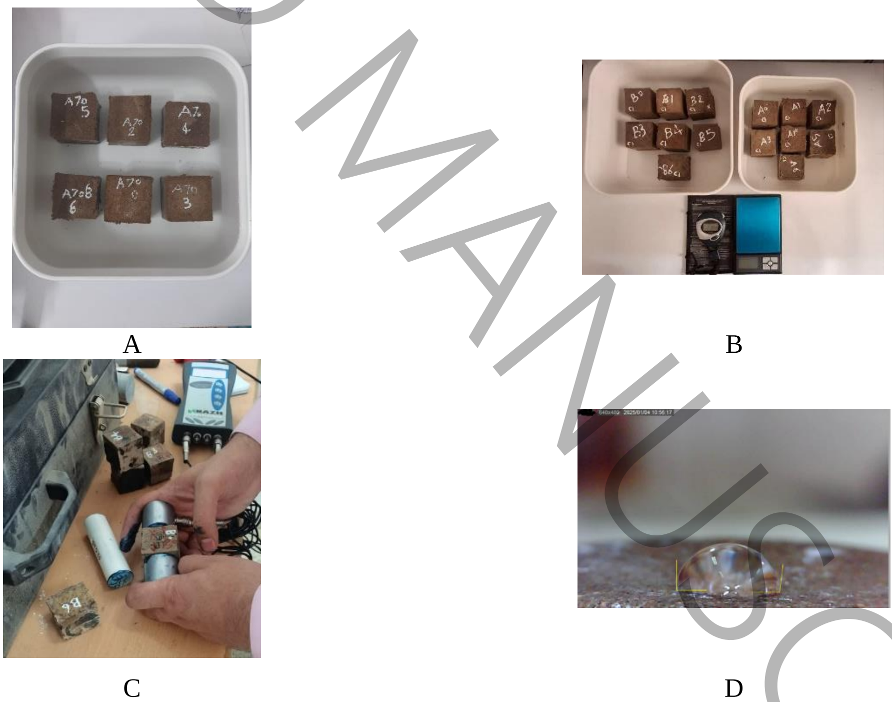


Figure 2. Experiments: A. Water absorption by an immersion method, B. Water absorption by a capillary method, C. Ultrasonic, D. Drop angle

2.3. Statistical analysis

In this study, to determine the relationships between the results of destructive and non-destructive tests, a statistical analysis was performed using the Response Surface Methodology (RSM) in the Design Expert software. The response surface methodology is a statistical-mathematical technique for optimizing a process, modeling the relationships between input and output variables, and reducing laboratory costs. Design Expert is also a specialized software program for experimental design and statistical data analysis, widely used in various engineering fields and process optimization. The modeling capabilities of this software were utilized in this research.

3- Results

3-1- Destructive test results

As mentioned earlier, the objective of this research was to establish a relationship between non-destructive and destructive durability tests to predict the durability properties of soil blocks stabilized with copolymer against weathering, including fluctuations in temperature, humidity, and rainfall conditions. This facilitates the estimation of the durability properties of stabilized soil blocks without resorting to costly and time-consuming destructive tests. Consequently, destructive tests were first conducted on the stabilized soil block specimens, the results of which are presented in Table 3.

According to the table, an increase in the polymer content leads to an improvement in durability properties, including erosion resistance, freeze-thaw cycles, and wet-dry cycles. This is because the increased polymer content reduces voids and porosity, thereby decreasing permeability and water absorption. Essentially, the polymer fills the soil voids and creates a continuous network, blocking the pathways for water ingress. Thus, a higher polymer content results in lower water absorption, which prevents soil swelling and expansion due to moisture [32]. Furthermore, in wet-dry cycles, reduced water penetration means lower stresses induced by the shrinkage and expansion of soil particles.

Additionally, increasing the polymer content enhances water-resistant bonds and, thus, improves resistance to water penetration. Since the primary damage in freeze-thaw cycles stems from the hydraulic pressure generated by the freezing of water in pores, the polymer reduces the porosity and water absorption, thereby limiting the volume of the water available to freeze and decreasing the internal pressure. Polymers also increase the flexibility of the soil matrix, reducing the cracking caused by the expansion of ice[33], [34].

3-2- Non-destructive test results

In this study, water absorption tests were conducted using both immersion and capillarity methods, alongside ultrasonic testing, contact angle measurement, and image processing. This section elaborates on the obtained results.

3-2-1- Water absorption test results

Figure 3 presents the results of water absorption via the immersion and capillarity methods. The immersion water absorption is expressed as a percentage, while the capillarity absorption is represented by the capillarity coefficient. As shown in Figure 3, an increase in the polymer content leads to a reduction in water absorption. Specifically, from sample A0 to A6, the increase in the polymer resulted in a 93% decrease in the water absorption percentage and an 87.3% reduction in the capillarity coefficient. Similarly, for samples B0 to B6, the percentage decrease in the water absorption and capillarity coefficient was 86.8% and 81%, respectively.

This phenomenon can be attributed to a reduction in porosity caused by the increased polymer content. Polymers fill the fine pores of the soil, resulting in a denser block structure. The decreased porosity restricts the penetration and movement of water through the capillary network of the soil. In other words, the polymer creates a continuous coating that blocks water infiltration pathways, and the coating layer prevents the formation of hydrogen bonds between water and soil particles. Since the utilized polymers possess hydrophobic properties, they coat soil particles, reducing water-soil contact and limiting water absorption. Also, increasing the polymer content reduces the diameter of the capillaries, thus decreasing the capillary rise height. It is noteworthy that these findings are consistent with the results of previous research. For instance, in a 2023 study [23], waste plastics were melted to produce a recycled polymer for soil block stabilization. The researchers reported a significant decrease in the water absorption of the blocks stabilized with an increased polymer content.

According to Figure 4, the trend of water absorption variation with the increasing polymer content mirrors the trend observed in the durability tests. As the polymer content increases, the weight loss due to wet-dry and freeze-thaw cycles, as well as the erosion depth, decreases. Concurrently, the increased polymer content reduces the surface porosity and/or the diameter of the capillary pores in the blocks, leading to decreased water absorption and a lower capillarity coefficient, thereby enhancing the durability of the block. In essence, it can be concluded that a reduction in water absorption directly correlates with an improvement in the durability properties of blocks.

Table 3. Destructive testing results

Mechanical test results				
Sample name	Brick weight loss due to freeze-thaw cycle **(%)**	Flooring weight loss due to freeze-thaw cycle (%)	Block weight loss due to wet-dry cycle (%)	Depth of hole due to erosion (mm)
A0	1.564522	1.991777	١,٠٤	٥,٣
A1	1.383039	1.827164	٠,٧٥	٣,٨
A2	0.730197	1.693548	٠,٦	١,٨
A3	0.667858	1.125742	٠,٤٥	١,١
A4	0.56	0.724458	٠,٣٦	٠,٥
A5	0.31	0.659062	٠,٢٢	٠
A6	0.2	0.498341	٠,١٨	٠
B0	1.8	3.16798	١,٣	١٦,٢
B1	1.102779	2.162146	٠,٩٨	١٠,١
B2	0.830197	1.489912	٠,٦٣	٦,٣
B3	0.767858	1.32602	٠,٥٢	٤,٦
B4	0.485939	0.948434	٠,٤٤	٠,٩
B5	0.34885	0.769189	٠,٢٥	٠
B6	0.28	0.593872	٠,١	٠

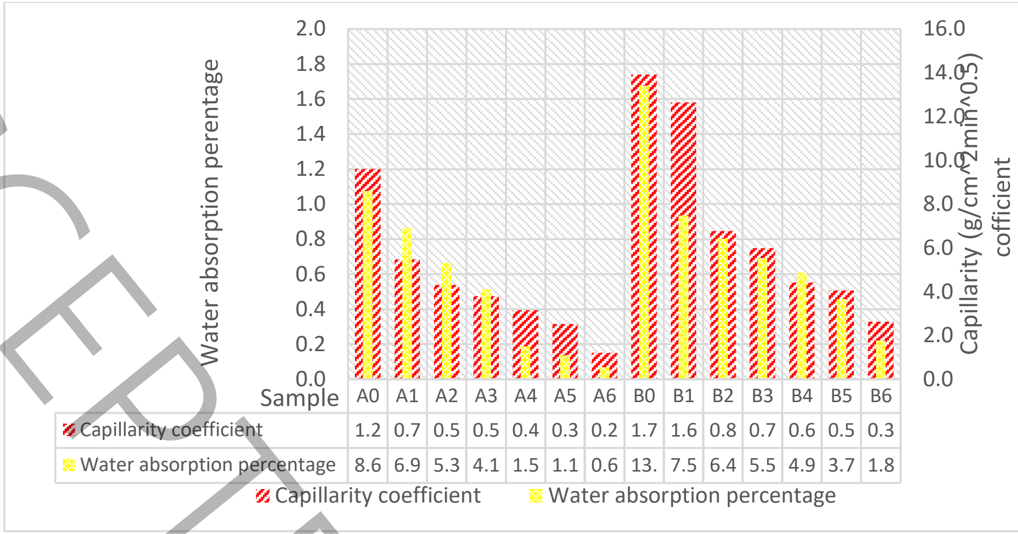
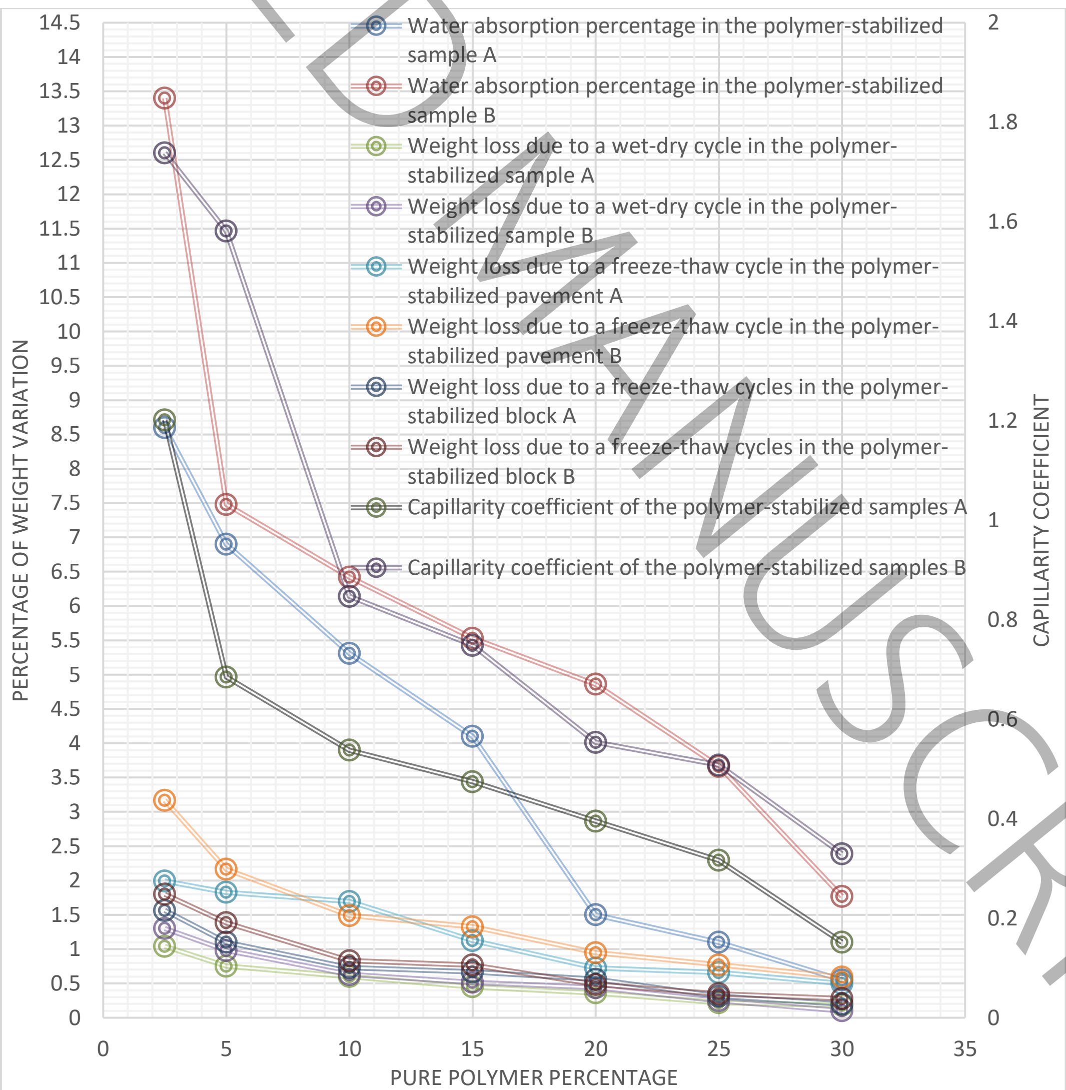


Figure 3. Results of the water absorption test



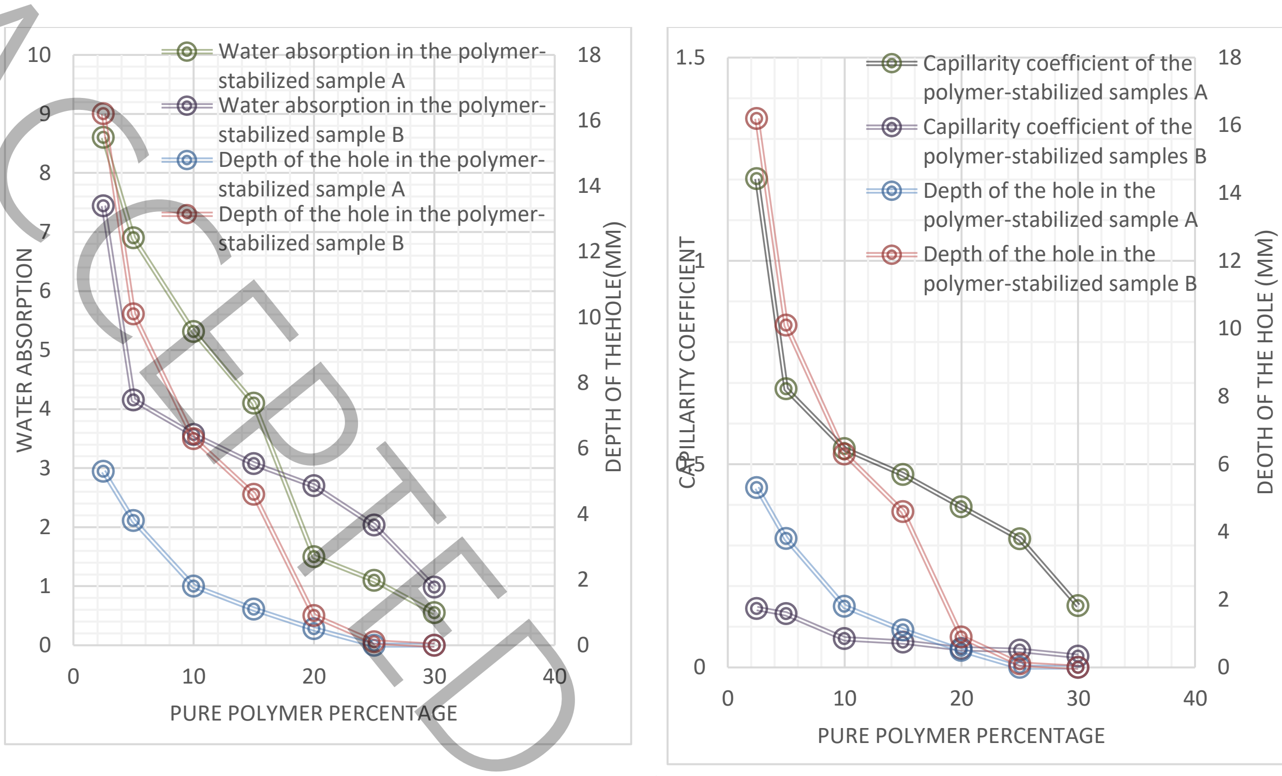


Figure 4. Comparison of the durability test results with water absorption

3-2-3- Ultrasonic test results

As mentioned, this test operates based on the velocity of sound waves in a material and their time of flight. Nowadays, it is widely used to assess the quality of construction materials. The results of the test are presented in Figure 5. According to the figure, the ultrasonic pulse velocity increases with a higher polymer content. This is because, as discussed in the previous section, an increase in the polymer content reduces the porosity of the sample. Specifically, the polymer fills the pores and voids within the material, resulting in a denser structure where air is replaced by polymer. Consequently, the velocity of sound waves increases. Furthermore, porous materials (such as dry soil) cause the scattering and absorption of sound wave energy. As the porosity reduces, the polymer decreases the wave attenuation and allows for more efficient transmission of the wave energy. These findings are consistent with the results of previous research. For instance, Satheepan et al. [35], demonstrated that increasing the cement content in cement-stabilized soil blocks leads to more filled pores and a consequent increase in ultrasonic pulse velocity.

According to Figure 6, the trend of wave velocity variation with the increasing polymer content is similar to the trend observed in the systematic durability tests. As the polymer content increases, the pulse velocity in the samples increases too, while the weight loss due to wet-dry and freeze-thaw cycles, as well as the erosion depth, decreases. As noted, an increased polymer content reduces the pores and voids of the sample that can be filled with water, while enhancing the cohesion of the sample. This process leads to improved durability. In general, it can be stated that an increase of wave velocity within a block correlates with an improvement in its durability properties.

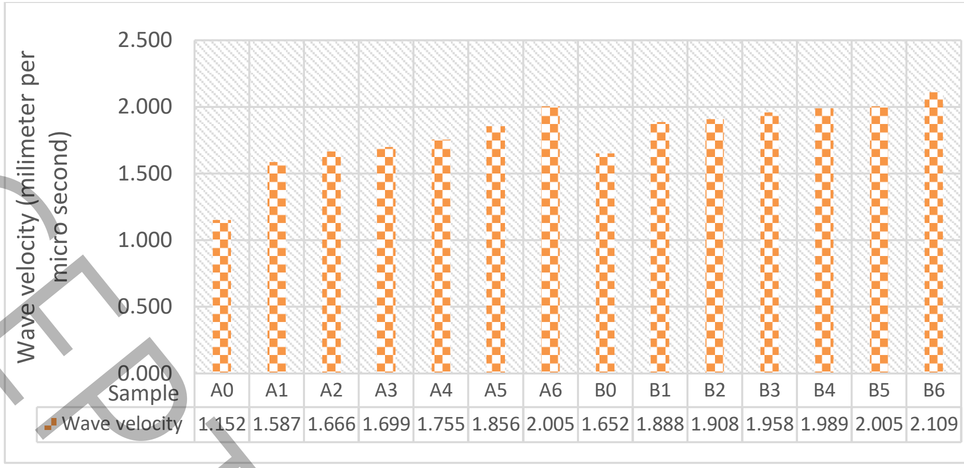
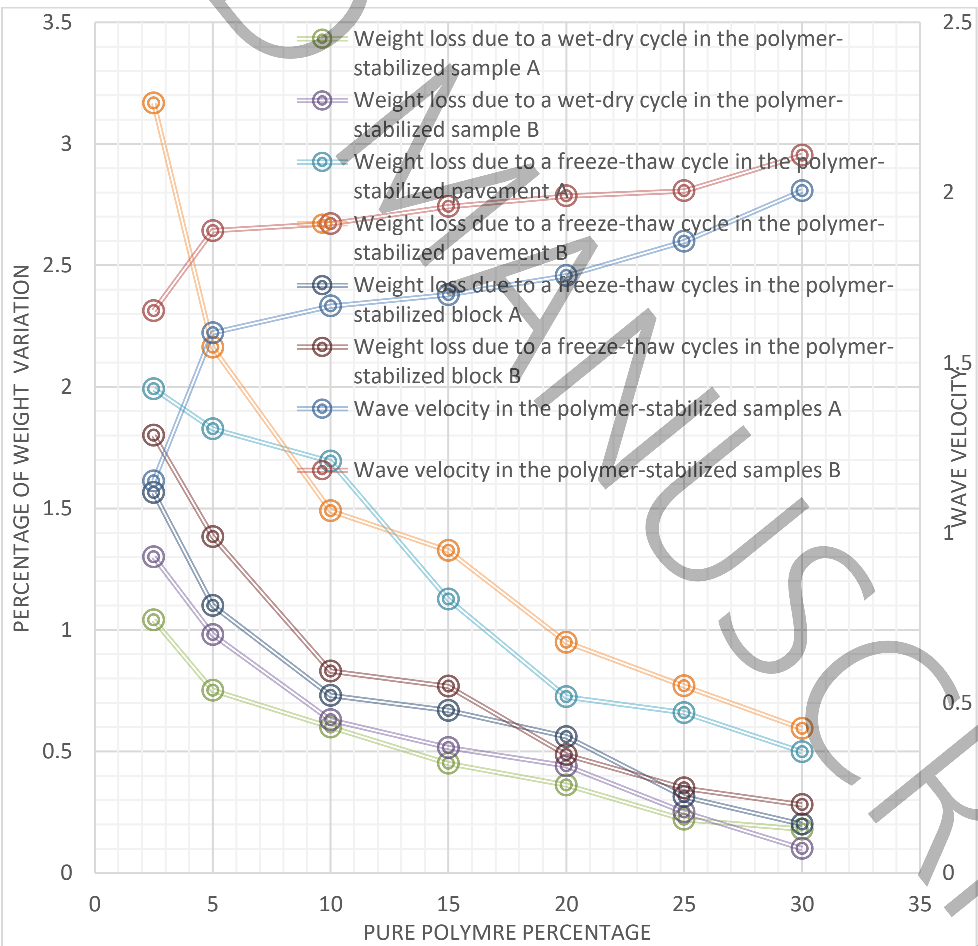


Figure 5. Ultrasonic test results



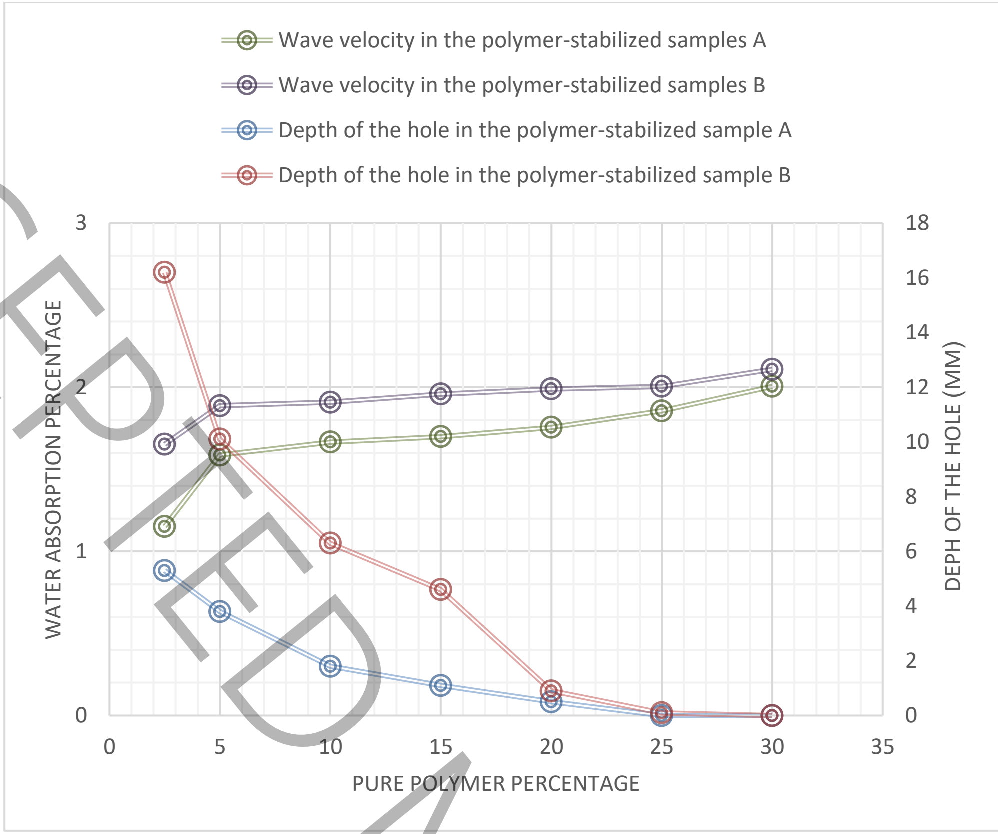


Figure 6. Comparison of durability and ultrasonic test results

3-2-4- Image processing results obtained with the MATLAB software

In this study, to investigate the surface pores and voids of the blocks, images were taken under consistent conditions using a mobile phone camera and subsequently processed with the MATLAB software. The surface porosity values obtained from the image analysis are presented in Table 5. According to this table and Figure 9, an increase in the polymer content led to a reduction in the pores and surface voids of the samples, which was accounted for in detail previously. The decrease in the block porosity enhanced resistance to wet-dry and freeze-thaw cycles. Furthermore, with an increased polymer content and reduced porosity, the cohesion and strength of the block improved, resulting in greater resistance to water pressure-induced erosion. The processed images are illustrated in Figure 11.

Table 4. Angle test results

Sample	Property	Sample	property
A0	hydrophilic	B0	hydrophilic
A1	hydrophilic	B1	hydrophilic
A2	hydrophilic	B2	hydrophilic
A3	hydrophilic	B3	hydrophilic
A4	hydrophilic	B4	Hydrophobic
A5	Hydrophobic	B5	Hydrophobic
A6	Hydrophobic	B6	Hydrophobic

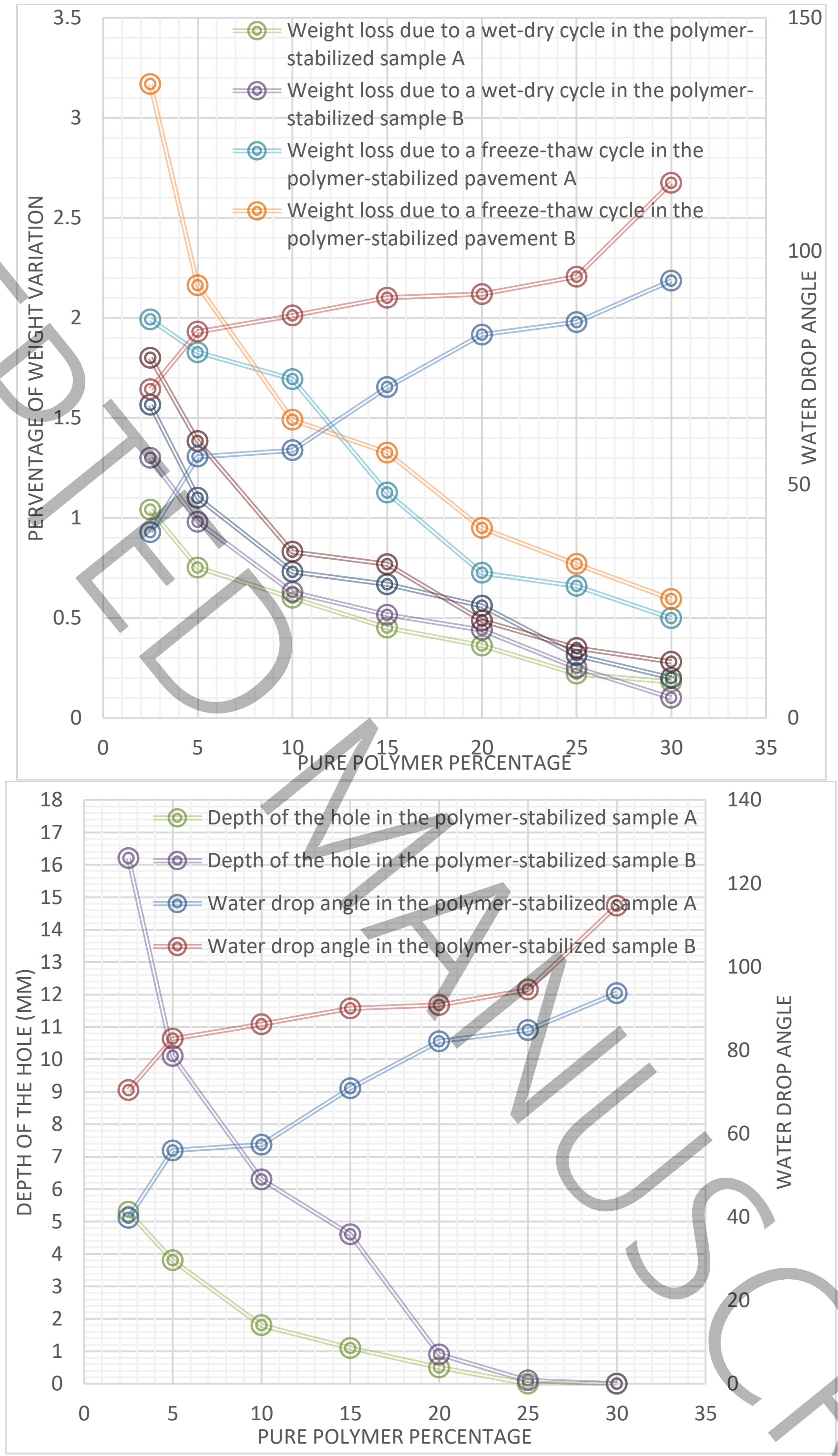
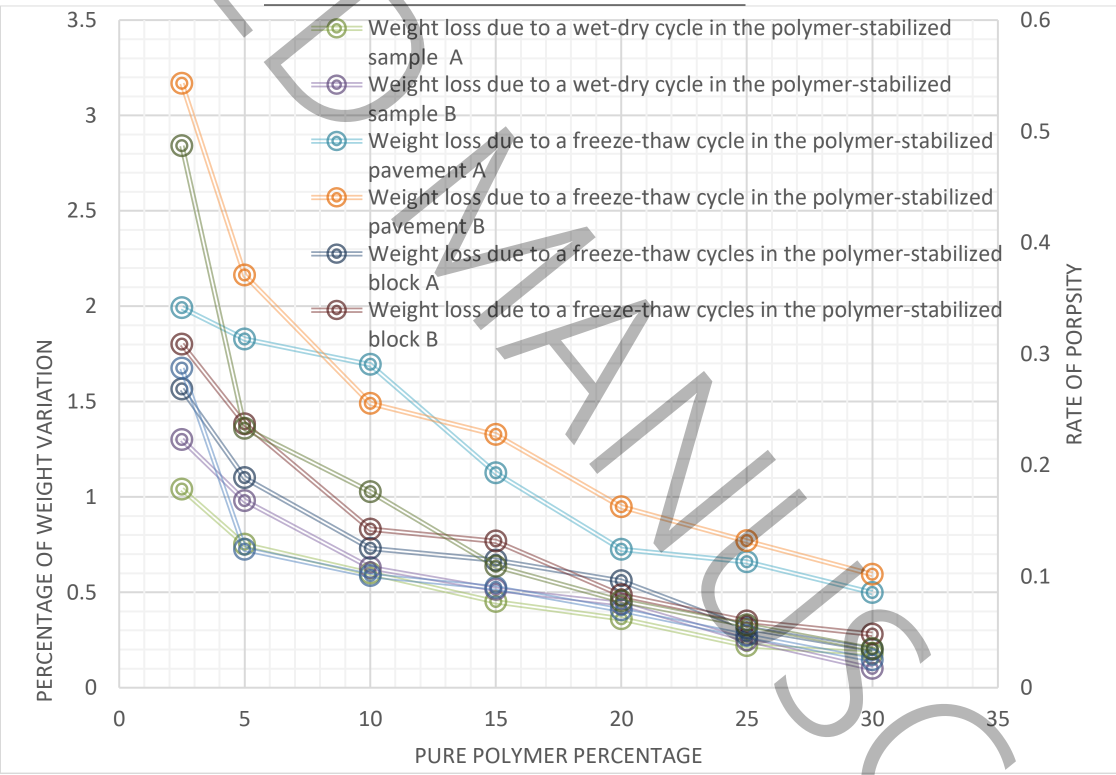


Figure 8. Comparison of durability test results with drop angle test findings

Table 5. Results of image processing with MATLAB

Sample	Rate of porosity	sample	Rate of porosity
A0	0.287	B0	0.487
A1	0.1243	B1	0.233
A2	0.1007	B2	0.176
A3	0.0899	B3	0.109
A4	0.0698	B4	0.078
A5	0.0468	B5	0.0562
A6	0.025	B6	0.0349



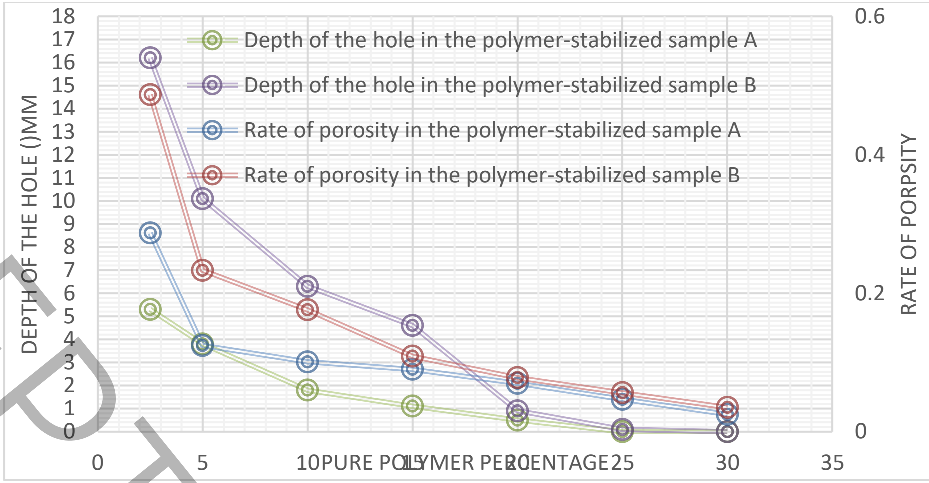


Figure 9. Comparison of durability test results with Rate of porosity findings

3-2-5- Statistical analysis

To determine the relationships between the results of the destructive and non-destructive tests and to predict the durability of the blocks against wet-dry cycles, freeze-thaw cycles, and rainfall-induced erosion, non-destructive tests were carried out and the response surface methodology (RSM) was employed via the Design Expert software. For this purpose, the results of the destructive tests, including freeze-thaw cycles for flooring, freeze-thaw cycles for non-load-bearing blocks, erosion, and wet-dry cycles, were defined as dependent variables. Also, the results of the non-destructive tests, including water absorption by immersion, water absorption by capillarity, ultrasonic testing, contact angle, and image processing, were defined as independent variables. The multivariate relationships and the coefficient of determination (R^2), which is one of the key metrics for assessing the quality of regression models, are presented in Table 6 .Furthermore, the three-dimensional variation plots of the variables are illustrated in Figure 11, indicating that the durability properties of the blocks improved with a decrease in water absorption percentage, capillarity coefficient and surface porosity as well as with an increase in contact angle and wave velocity. This is because reduced water absorption and surface porosity, along with increased wave velocity and contact angle, signify fewer air voids within the block, enhanced cohesion and integrity, and consequently, improved durability.

According to the relationships presented in Table 6, the coefficients of determination (R^2) for the proposed models are close to 1, demonstrating the strong explanatory power of the models. Using the equations provided in Table 6, the durability properties of the soil blocks stabilized with the investigated copolymers can be estimated with reasonable accuracy. However, applying these equations requires the simultaneous availability of the results from all non-destructive tests, i.e., water absorption by immersion, water absorption by capillarity, ultrasonic testing, contact angle, and surface porosity determination via image processing. The additional relationships between each dependent variable and the individual independent variables are provided in Table 7. Given that the proposed multivariate relationships exhibit high coefficients of determination, exceeding 0.9, the use of non-destructive methods and the application of these multivariate models are prioritized. However, in cases where conducting non-destructive tests is not feasible, single-variable relationships may serve as an alternative approach. Among these, the relationships based on water absorption and capillary coefficient tests show coefficients of determination greater than 0.8. Between the two, considering the faster execution of the capillary coefficient test, its results are recommended for predicting the performance of the blocks.

Table 6. Multivariate relationships between the independent and dependent parameters

Relationships	R^2
Hole depth = -15.925 - 0.1844*W + 3.5410*C + 11.855*S-0.099*D + 32.715*P	٠,٩٧٤
Wet and dry cycle weight loss = 0.364 + 0.0137*W +0.38*C + 0.233*S - 8.1569E-003*D +0.59*P	٠,٩٨٩
Weight loss of paving freeze-thaw cycle = -0.436 + 0.065*W + 0.355*C + 1.581*S - 0.025*D + 2.498*P	٠,٩٧٤
Weight loss of brick freeze-thaw cycle = 1.305 + 0.030*W + 0.643*C - 0.601*S6.336E - 004*D - 2.232E - 003*P	0.982

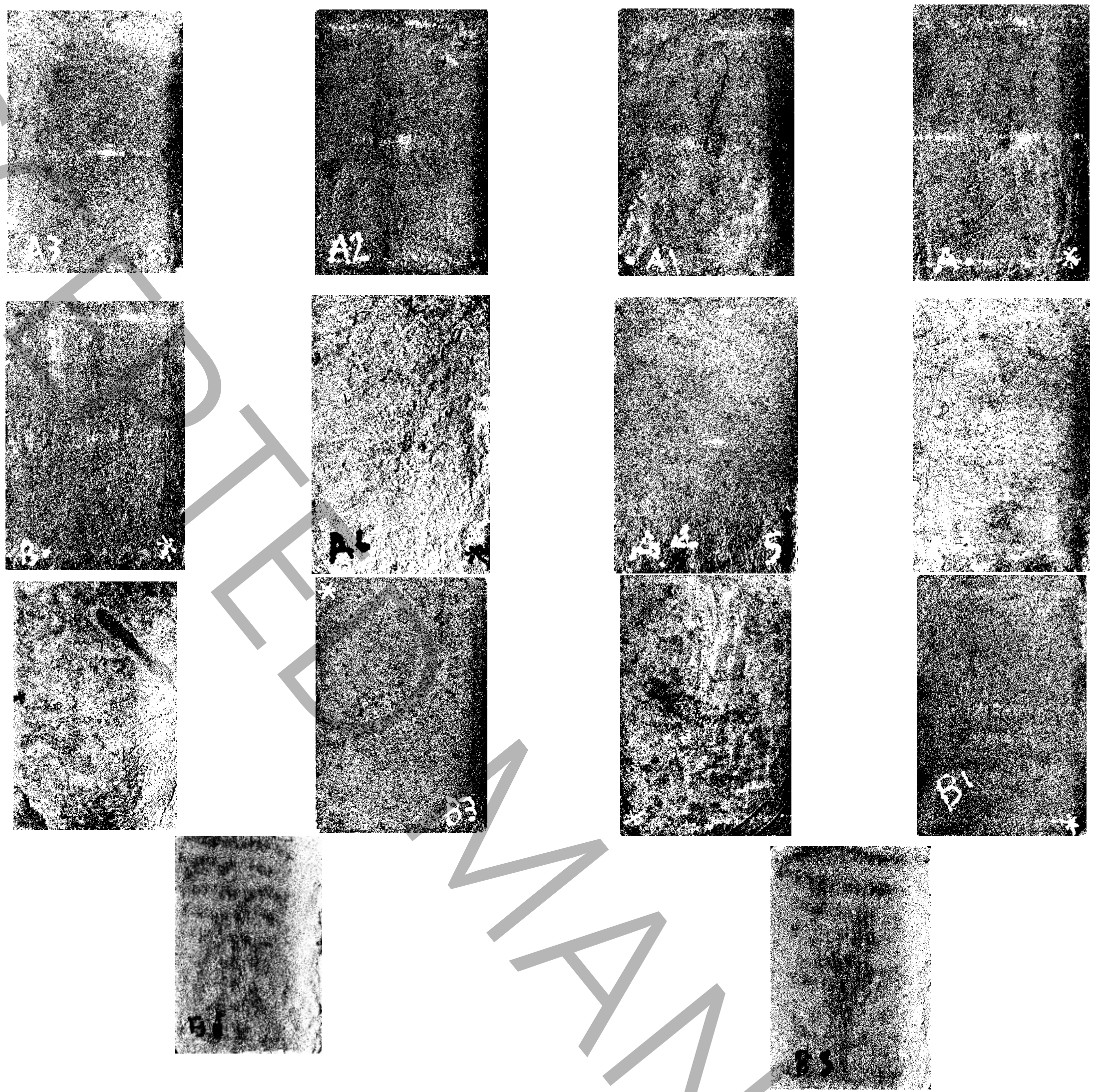


Figure 10. Image processing with MATLAB

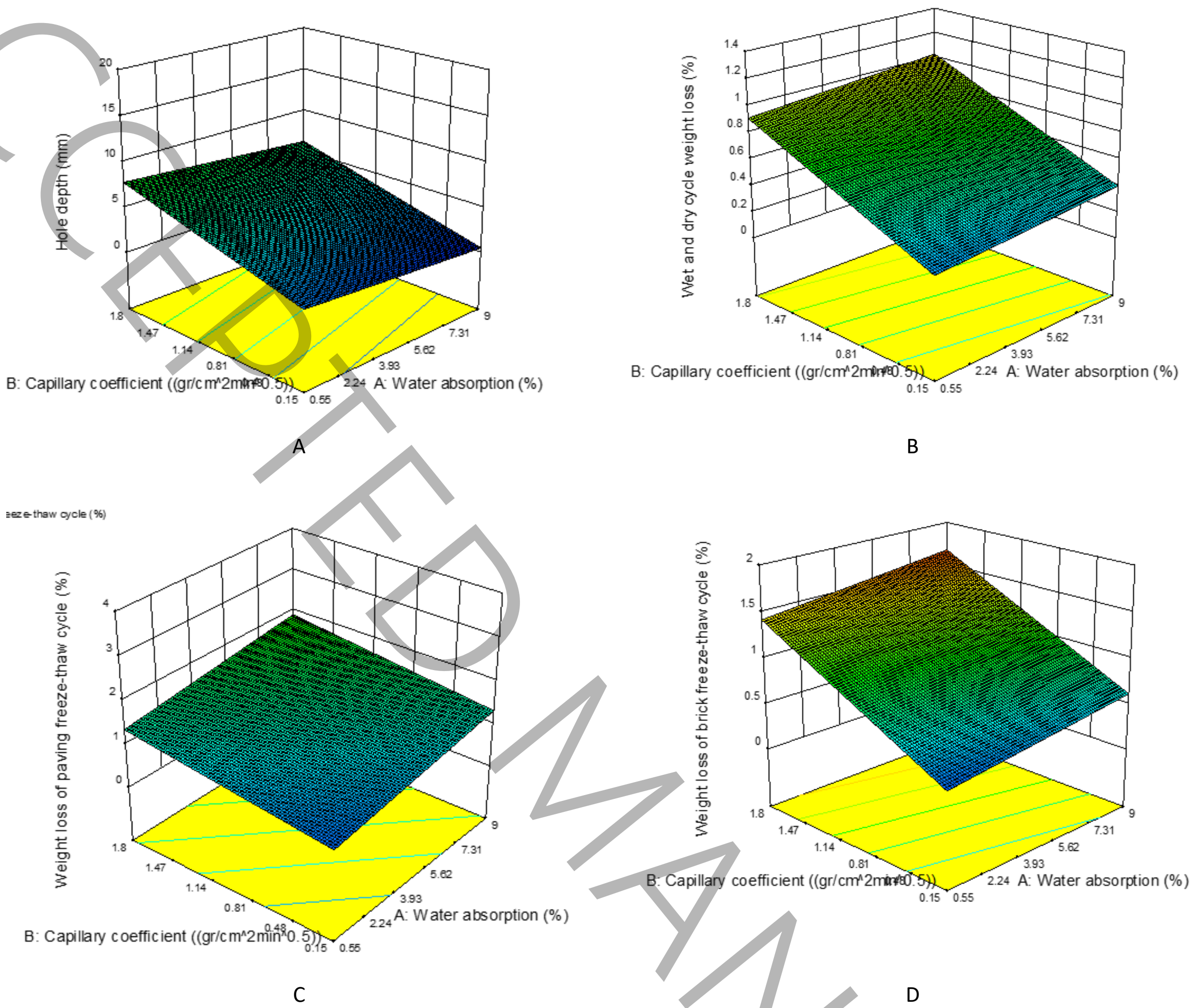


Figure 11. Three-dimensional diagrams of the presented relationships

Table 7. Univariate relationships between the dependent variable and the independent variable

Relationships	R^2
Hole depth = - 2.6434 + 1.2322 * W	٠,٨١7
Wet-dry cycle weight loss = + 0.06363 + 0.0973 * W	٠,٩٠٣
Weight loss of paving freeze-thaw cycle = + 0.2812 + 0.2112 * W	٠,٩٣٣
Weight loss of brick freeze-thaw cycle = + 0.1017 + 0.1349 * W	0.8701
Hole depth = - 3.1458 + 9.4103* C	0.898
Wet-dry cycle weight loss = + 0.0567 + 0.6975*C	٠,٨٧٥
Weight loss of paving freeze-thaw cycle = + 0.3024 + 1.464*C	٠,٨٤٥
Weight loss of brick freeze-thaw cycle = + 0.0802 + 0.9841*C	٠,٨٧٢
Hole depth = + 14.328 - 5.9412*S	0. 750
Wet-dry cycle weight loss = + 2.2554 - 0.94172076*S	٠،68٢
Weight loss of paving freeze-thaw cycle = + 4.4532 - 1.7188*S	٠،7٠٩
Weight loss of brick freeze-thaw cycle = + 3.2986 - 1.3931*S	٠،6٦٣
Hole depth = + 9.6759 - 0.0761*D	0.750
Wet-dry cycle weight loss = + 1.5378 - 0.0123*D	0.643
Weight loss of paving freeze-thaw cycle = + 3.235 - 0.0236*D	0.757
Weight loss of brick freeze-thaw cycle = + 2.1609 - 0.0172*D	0.683
Hole depth = + 3.442 + 1.32*P	0.704
Wet-dry cycle weight loss = + 0.506 + 0.388*P	0.626
Weight loss of paving in a freeze-thaw cycle = + 1.307 + 0.356*P	0.717
Weight loss of block in a freeze-thaw cycle = + 0.704 + 0.62*P	0.683

It should be noted that in the presented relationships, W denotes the water absorption percentage due to immersion, C is the capillary coefficient in units of gr/cm^2min^0.5, S represents the wave velocity in mm/s, D is the droplet contact angle in degrees, and P corresponds to the surface porosity derived from image processing.

According to the coefficients of determination for the relationships presented in Table 7, although the determination coefficients of the univariate relationships are mostly above 0.6 and considered acceptable, the coefficients of determination for the multivariate models exceed 0.9, indicating higher reliability. Therefore, multivariate relationships are recommended for more accurate prediction of the durability properties of copolymer-stabilized earthen blocks. However, when there are constraints on resources, time, or the project sensitivity is low, single non-destructive tests combined with univariate models can provide reasonably accurate estimates of the durability properties. In general, predicting the durability properties of stabilized earthen blocks using relationships and models based on non-destructive tests has several significant advantages, including:

- Preservation of samples (non-destructive nature),
- Time and cost savings,
- The possibility of continuous monitoring and quality control during construction,
- On-site applicability,
- Reduction of material wastage,
- And environmental compatibility.

Regarding the non-destructive nature, these tests do not damage the samples, allowing them to be reused after testing — a valuable feature when samples are limited or expensive. Moreover, non-destructive methods are generally faster and less costly than destructive ones and reduce the need for producing multiple samples for various tests. Concerning continuous monitoring and quality control during construction, since the samples remain intact, the material properties can be evaluated at different construction stages and even after the structure has been completed. This capability is particularly beneficial for large-scale and long-term projects. Additionally, many non-destructive techniques, such as ultrasonic testing, can be applied in situ, which is highly practical for assessing existing structures or ongoing construction projects. Furthermore, because samples are not destroyed, material waste is minimized, aligning well with sustainable development principles and green construction practices. In conclusion, the use of prediction models based on non-destructive tests provides a cost-effective, rapid, sustainable, and accurate method for assessing the durability properties of stabilized earthen blocks, proving especially useful for large-scale projects and long-term research.

The results of this study also indicate that the use of non-destructive tests such as water absorption measurement, ultrasonic pulse velocity, droplet contact angle, and image processing, combined with statistical models based on Response Surface Methodology, can provide an efficient and cost-effective tool for predicting the durability of earthen blocks stabilized with synthetic copolymers. This approach is particularly suitable for large-scale projects that require extensive and rapid durability assessments and could serve as a viable alternative to traditional destructive testing methods. The application of these findings can assist construction companies and materials engineers in reliably and economically evaluating the quality of building blocks by reducing the number of destructive tests, thereby saving time and costs. Furthermore, the presented multivariate models are capable of reflecting the effects of various manufacturing conditions and additive contents, enabling optimization of the material production process. In cases of limited resources, simpler univariate relationships with lower accuracy are considered practical alternatives. Therefore, it is recommended that in large-scale projects, these non-destructive testing methods, combined with appropriate statistical models, be integrated into the material quality assurance system to better control durability, reduce implementation costs, and accelerate construction processes.

It should be noted that the models developed in this study are based on experiments conducted exclusively on the sand used in the investigation and with two emulsion copolymers—styrene–acrylate (A) and styrene–butadiene (B)—within a polymer content range of 2.5 to 30 percent by weight. Therefore, the validity of the results is limited to this specific polymer content range and this particular soil type. Considering that soil–polymer behavior depends strongly on the soil's characteristics and the chemical structure of the polymer, applying these models to different soils or polymers, or to polymer contents outside the aforementioned range, requires recalibration and additional complementary testing.

4- Conclusion

Stabilized soil blocks represent an environmentally friendly construction material, produced by mixing appropriate proportions of non-expansive clay, sand, aggregates, and moisture, followed by manual or electric compaction and stabilization with various additives. The durability of stabilized soil blocks ensures structural stability, reduces maintenance costs, and supports environmental conservation. Therefore, durability parameters such as resistance to freezing, moisture, and erosion must be carefully evaluated during the design and construction of these blocks .Predicting the durability properties of stabilized soil blocks using the models based on non-destructive testing offers an efficient, cost-effective, and sustainable approach applicable during the design, construction, and maintenance phases of structures. These methods are particularly valuable for large-scale projects and in regions with harsh environmental conditions, such as humid or frozen areas. In this study, destructive and non-destructive tests were conducted to determine the relationships that help to predict the durability properties of emulsion copolymer-stabilized soil blocks using non-destructive test results. The key findings of this research are as follows:

- Increasing the polymer content in stabilized soil blocks improves durability properties, including resistance to wet-dry cycles, freeze-thaw cycles, and erosion.

- A higher polymer content reduces water absorption, with samples A0 to A6 showing a 93% decrease in water absorption percentage and an 87.3% reduction in the capillarity coefficient. Similarly, for samples B0 to B6, the decreases were 86.8% and 81%, respectively.

- Ultrasonic wave velocity increases with a higher polymer content, as the polymer fills pores and voids, resulting in a denser structure.

- An increased polymer content reduces the hydrophilicity of the blocks, imparting hydrophobic properties. Image processing results further confirm a reduction in surface pores and porosity with a higher polymer content.

- The study demonstrates that reduced water absorption and surface porosity, along with increased wave velocity and contact angle, improve the block cohesion, fewer internal voids, and discontinuities, leading to enhanced durability.

- Multivariate and univariate relationships between destructive durability tests and non-destructive tests, developed with the response surface methodology, are presented in Tables 6 and 7. Based on the comparison of determination coefficients (R^2), the use of multivariate relationships is recommended.

- For projects with limited resources and time, or lower sensitivity, a single non-destructive test combined with univariate relationships can provide acceptable accuracy in estimating the durability properties of copolymer-stabilized soil blocks.

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