Research Article

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Optimizing Manufacturing Parameters Of Tiles Produced From Recycled Thermoplastic Waste And Household Refused Incineration Ash.

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ABSTRACT

To address the excessive accumulation of plastic waste and incineration ash from domestic refuse, this study explores their use in tile manufacturing. The goal is to optimize manufacturing conditions—mixing temperature, mixing time, and compression force—using the Box-Behnken design and Response Surface Methodology (RSM). Tiles were produced at temperatures of 200, 210, and 220°C, with mixing times of 10, 15, and 20 minutes, and compression forces of 120, 135, and 150 tons. The results showed high coefficients of determination (R^2) for compressive strength, flexural strength, and surface abrasion resistance, with an average error of less than 5%. The optimal conditions identified were a mixing temperature of 210°C, a mixing time of 15 minutes, and a compression force of 135 tons, yielding tiles with a compressive strength of 18.25 MPa, a flexural strength of 10.10 MPa, and a surface abrasion resistance of 0.02 g/cm².

Keywords : *Optimization, Response Surface Methodology (RSM), recycled plastic waste, ash, incinerated household waste.*

INTRODUCTION

Globally, energy consumption, CO2 emissions, depletion of natural resources, and plastic waste are significant environmental issues. The demand for plastics has increased significantly in recent decades, leading to approximately 300 million tons of plastic waste being generated annually [1, 2]. Various initiatives have been implemented to reduce plastic waste accumulation, such as recycling and banning single-use plastics. However, recycling thermoplastic waste remains inefficient due to labor-intensive processes and low recycling rates, with only about 10% of total plastic waste being recycled [3]. Utilizing simple recycling processes, such as cleaning and shredding to produce raw materials for construction and insulation, is more appealing to recycling companies and consumers. Despite their low biodegradability and inability to decompose naturally [4, 5], plastics have beneficial properties such as light weight, low water absorption, high compressive strength [6, 7], high chemical resistance, weather resistance, insulation properties, and low cost [8, 9]. Furthermore, replacing traditional materials with lighter and cheaper materials not only saves production and transportation costs [10] but also reduces the mass and weight of construction projects, thus lowering the structural load. This concept of using plastics as a substitute material in construction has emerged [11]. Nowadays, many studies support the reuse of plastic waste in building materials. Recycling polyethylene (PE) and polypropylene (PP) plastics is preferred over other thermoplastics because they not only constitute a large proportion of household waste but also have low melting points [12].

The use of incineration technology to process municipal solid waste is becoming a common trend worldwide due to benefits such as volume reduction, land conservation, reduced leachate and odor, and energy recovery for electricity production. However, this process generates a large amount of solid waste in the form of ash. This ash is not considered hazardous waste and can be reused as a potential raw material in the production of building materials [13]. Researchers have made efforts to utilize this ash in building materials. For example, Huỳnh Trọng Phước et al. developed self-compacting concrete blocks using incineration ash that met technical standards for water absorption and surface abrasion resistance with grades M300 – M500 [14]. However, this method still uses traditional materials such as cement, sand, and water.

Plastic waste, especially thermoplastic waste, has also received significant attention for recycling and reuse, being considered a valuable resource. In 2017, Nguyễn Võ Châu Ngân et al. proposed a solution to process plastic waste into granular material for mixing with concrete. In Kenya, plastic

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waste is shredded and mixed with sand at 350°C to produce paving blocks using a hot-pressing method [5]. In 2019, M.K. Mondal et al. used 10% thermoplastic waste and 60%-70% fly ash with 15% ordinary Portland cement to produce paving blocks [16]. Similarly, Rajarapu Bhushaiah et al. used thermoplastic with fly ash, cement, and sand in the production of paving blocks [17]. Ilyas Ennahal et al. created materials using 70% minerals (sediments) and 30% thermoplastic waste containing polypropylene, polyethylene, and polystyrene [18]. Recycling polyethylene (PE) and polypropylene (PP) plastics is prioritized over other types of thermoplastics because they not only constitute a large proportion of household waste but also have low melting points [19].

Although there have been many inventions and solutions using fly ash from power plants to produce building materials, such as fillers in artificial stone, cement, and paving blocks from fly ash and plastic waste, the use of incineration ash and thermoplastic waste from municipal waste treatment plants to produce paving blocks by hot-pressing has not been reported.

Typically, clay, sand, and cement are commonly used to produce paving blocks. However, this study replaces these materials with recycled thermoplastic waste and ash from municipal waste incineration. This represents a further step towards a circular economy and environmental protection. The production parameters of paving blocks from recycled thermoplastic waste and incineration ash using the hot-pressing method, such as mixing temperature, mixing time, compression force, etc., significantly affect the properties of the product. To achieve suitable conditions for the production of paving blocks and obtain products with good, stable properties, careful selection of production parameters is necessary. A traditional method for optimizing production parameters is the one-variable-at-a-time approach. In this method, each experiment is designed to include one variable change while other parameters are kept constant, and experiments are repeated with different variable changes each time. However, this method is costly and time-consuming and does not achieve truly optimal values. Therefore, using statistical tools such as the response surface method with the Box-Behnken design can help alleviate and address many optimization challenges. The Box-Behnken experimental design allows for the simultaneous evaluation of the combined effects of different parameters such as mixing temperature, mixing time, compression force, etc., at various levels on the compressive strength, flexural strength, and surface abrasion resistance of paving blocks.

This study is novel in that it specifically explores the optimal production conditions for paving blocks made from the combination of recycled thermoplastic waste and municipal incineration ash, a relatively unexplored area. Previous studies have often focused on the use of either recycled plastic or incineration ash independently, rather than in combination. The results from these studies show varying degrees of success in improving material properties but do not comprehensively address the combined effects of these two types of waste. By identifying optimal parameters using the Box-Behnken design, this study makes a significant contribution to the field of sustainable building materials, providing a feasible solution for waste management and material innovation.

EXPERIMENT

Raw materials and chemicals

- Incineration ash from the household waste treatment of APT
- Seraphin Hai Duong Environmental Joint Stock Company.
- Recycled thermoplastic waste from the household waste treatment of APT - Seraphin Hai Duong Environmental Joint Stock Company, with chemical composition including polyethylene (PE - 97.82%); polypropylene (PP - 2.18%).
- Thermal stabilizer commercial product (from China), Mold stabilizer (from China), and Mold release agent (from China).

Methods of fabrication and analysis of the physical properties of the tiles

The tiles were manufactured using hot-melt extrusion on a twin-screw extruder with a ratio of recycled thermoplastic waste/ waste incineration ash/ additives = 60/40/3. The technical parameters for tile fabrication were adjusted according to Table 2.

The produced tile samples were determined and analyzed for various indicators such as: surface mass loss abrasion resistance according to TCVN 6065:1995, flexural strength according to standard TCVN 6355:2009. Additionally, assessments were made on edge length deviation, edge straightness, surface flatness, cracks, surface layer cracks, and edge surface crack according to standard TCVN 7744:2013. Heavy metal content was determined according to JIS 5741:2016 standard.

Statistical analysis of experimental results

Variance analysis, regression analysis, model determination, response surface analysis, and optimization were all performed on the experimental data obtained. ANOVA (Analysis of Variance) is an objective decision-making tool based on statistics, evaluated by regression coefficients, F-values, P-values, and correlation coefficient R.

Methods for Analyzing the Composition of Harmful Substances

The method for analyzing leachate solutions in QCVN 07: 2009/BTNMT aims to determine the potential release of hazardous components from waste under natural conditions.

Waste samples are prepared and leached, with liquid waste (solid content < 0.5%) filtered through a glass fiber filter and used directly for analysis. For solid or sludge waste (solid content ≥ 0.5%), the solid fraction is separated, mechanically treated, and leached using an acidic solution prepared from CH3COOH and water, with a 20:1 ratio to the solid waste mass, over 18 ± 2 hours. The leachate solution is then analyzed to determine the concentration of hazardous components, using methods ASTM D5233-92 or EPA 1311 (TCLP). The analysis results are calculated using the formula Ctb = (Vl * Cl + Vnc * Cnc) / (Vl + Vnc) to determine the average leachate concentration of the hazardous components.

RESULTS AND DISCUSSION

Experimental results

Analysis of the components of some harmful substances and the structural morphology of waste incineration ash

In practice, there have been studies utilizing this type of ash in agriculture for soil improvement, in industrial materials, and for environmental restoration in some limestone quarrying mines. However, the consumption rate is still low due to the perception that this ash is hazardous waste containing toxins or radiation. Therefore, this work conducted an analysis of the components of harmful substances in the ash samples from the waste incineration facility before applying in tile manufacturing. The components of some harmful substances in the incineration ash from the waste disposal facility were presented in **Table 1**.

Table 1. Components of some harmful substances in the incineration ash from the waste disposal facility.

Hazardous component	Content (mg/l)			QCVN07:2009/BTNMT Soaking extraction concentration (mg/L)
	Sample 1	Sample 2	Sample 3	
Lead (Pb)	< 0,005	< 0,005	< 0,005	15
Cadmium (Cd)	< 0,005	< 0,005	< 0,005	0,5
Mercury (Hg)	< 0,003	< 0,003	< 0,003	0,2
Selenium (Se)	0,048	0,054	0,047	1
Arsenic (As)	0,007	0,032	0,024	2
Chromium (VI)	< 0,15	< 0,15	< 0,15	5

The results in Table 6 showed that the concentrations of hazardous substances in the incinerated waste ash were extremely low and meet the standards of QCVN07:2009/BTNMT. This indicated that this source of ash can be fully utilized in the production of tiles and some other construction materials without causing harm to the environment.

SEM images of the incinerated waste ash were presented in **Figure 1 (A)**. As observed, the particles of household waste incinerator ash were irregular, fragmented, and porous. SEM images of the incinerated waste ash show that the particles are irregular, fragmented, and porous. The irregular shape and porosity help increase surface area, improving adhesion in composite materials. However, fragmentation and uneven particle size can create weak points, reducing the homogeneity and mechanical strength of the final product. The particle size distribution indicates the presence of both small and large particles, creating a wide size range. This uneven size distribution can affect the dispersion and integration of ash in composite materials, leading to inconsistent mechanical properties. High porosity can enhance the thermal and acoustic insulation properties of the material but may also reduce mechanical strength if the pores are too large or unevenly distributed. Incinerated waste ash shows advantages in insulation properties but requires optimization to improve mechanical strength.

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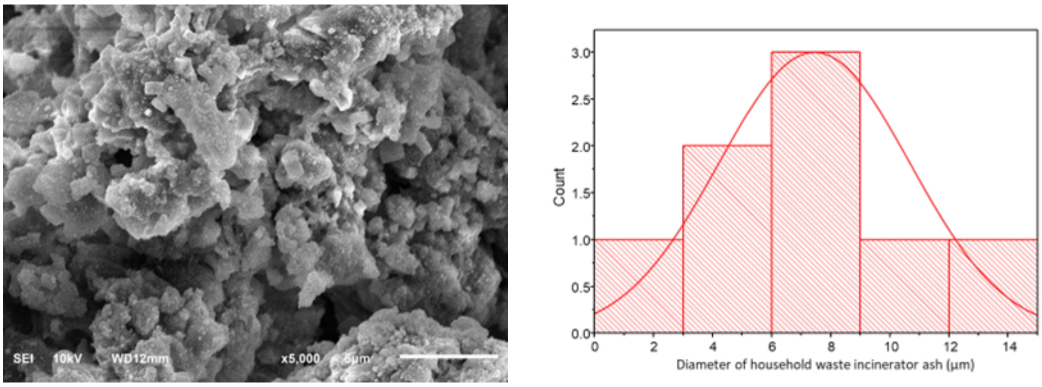
Figure 1. (A) SEM images and (B) particle size distribution of the waste incineration ash.



A B

Analysis of the influence of technological parameters on the mechanical properties of tiles

Effects of Mixing Temperature, Time, and Compression Force on the Compressive Strength of Paving Blocks Made from Recycled Thermoplastics and Incineration Ash

The paving blocks were manufactured using a hot-melt mixing method in a twin-screw extruder with a waste thermoplastic/incineration ash/additive ratio of 60/40/3. The technical parameters for producing the paving blocks were adjusted as follows:

Table 2. Effect of Mixing Temperature on Compressive Strength.

Mixing Temperature (°C)	Mixing Time (minutes)	Compression Force (tons)	Compressive Strength (MPa)
120	20	150	11.17
150	20	150	12.4
180	20	150	14.26
210	20	150	16.21
240	20	150	15.79

The results show that the compressive strength gradually increases as the mixing temperature rises from 120°C to 210°C, reaching a maximum value of 16.21 MPa at 210°C. However, when the mixing temperature continues to increase to 240°C, the compressive strength slightly decreases to 15.79 MPa. This indicates that excessively high mixing temperatures can reduce the compressive strength of the product.

Table 3. Effect of Mixing Time on Compressive Strength

Mixing Temperature (°C)	Mixing Time (minutes)	Compression Force (tons)	Compressive Strength (MPa)
210	10	150	14.08
210	15	150	16.94
210	20	150	16.18
210	25	150	15.48
210	30	150	15.57

The results indicate that the compressive strength reaches its highest value of 16.94 MPa when the mixing time is 15 minutes. When the mixing time exceeds 15 minutes, the compressive strength tends to decrease. This suggests that the optimal mixing time to achieve the highest compressive strength is 15 minutes.

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Table 4. Effect of Compression Force on Compressive Strength.

Mixing Temperature (°C)	Mixing Time (minutes)	Compression Force (tons)	Compressive Strength (MPa)
210	15	120	16.87
210	15	135	18.19
210	15	150	16.99
210	15	165	15.37
210	15	180	13.78

The results show that the compressive strength reaches its highest value of 18.19 MPa when the compression force is 135 tons. When the compression force exceeds 135 tons, the compressive strength decreases. This indicates that the optimal compression force to achieve the highest compressive strength is 135 tons.

Based on the results from the three tables above, the optimal conditions to achieve the highest compressive strength for paving blocks made from waste plastics and incineration ash are:

- Mixing Temperature: 210°C
- Mixing Time: 15 minutes
- Compression Force: 135 tons

These conditions yield the highest compressive strength of 18.19 MPa. Additional experiments should be conducted to test other properties of the product, such as flexural strength and abrasion resistance, to ensure that the product meets the necessary quality standards for practical applications.

Experimental Design

The Box-Behnken design is a Response Surface Methodology (RSM) approach used in experimental design. In this study, technological parameters including mixing temperature (A, °C), mixing time (B, minutes), and compression force (C, tons) were investigated. Through the use of mathematical and statistical methods, the RSM approach explores the factors that may influence various variables. The different technological conditions of the experiment were presented in **Table 5**. The Design Expert software was used as a statistical analysis tool.

Table 5. Technical parameters used in the experiment.

Technical parameters	Variation range (Δ)	Technological conditions		
		-1	0	1
Mixing temperature, oC, (A)	10	200	210	220
Mixing time, minutes (B)	5	10	15	20
Pressure, tons (C)	15	120	135	150

To investigate the influence of technological parameters on the material fabrication process, 15 different experiments were conducted (**Table 6**) and evaluated using various methods.

Table 6. Experimental results obtained under different technological conditions

N.O	Mixing temperature, oC (A)	Mixing time, minutes (B)	Pressure, tons (C)	Compressive strength (MPa)	Flexural strength (MPa)	Surface abrasion resistance (g/cm2)
1	200	15	150	17.25(±0.087)	9.78(±0.032)	0.011(±0.0004)
2	210	15	135	18.25(±0.087)	10.1(±0.032)	0.02(±0.0004)
3	200	15	120	15.05(±0.087)	9.25(±0.032)	0.017(±0.0004)
4	210	20	120	16.73(±0.087)	9.17(±0.032)	0.009(±0.0004)
5	200	10	135	16.52(±0.087)	9.61(±0.032)	0.018(±0.0004)
6	200	20	135	17.41(±0.087)	9.92(±0.032)	0.012(±0.0004)
7	210	15	135	18.25(±0.087)	10.1(±0.032)	0.02(±0.0004)
8	210	20	150	17.54(±0.087)	9.82(±0.032)	0.007(±0.0004)

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9	210	15	135	18.25(±0.087)	10.1(±0.032)	0.02(±0.0004)
10	220	20	135	18.06(±0.087)	9.85(±0.032)	0.013(±0.0004)
11	210	10	150	17.33(±0.087)	9.5(±0.032)	0.012(±0.0004)
12	220	10	135	17.92(±0.087)	9.98(±0.032)	0.019(±0.0004)
13	210	10	120	16.04(±0.087)	9.2(±0.032)	0.016(±0.0004)
14	220	15	150	17.19(±0.087)	9.9(±0.032)	0.015(±0.0004)
15	220	15	120	17.07(±0.087)	9.47(±0.032)	0.014(±0.0004)

Analysis of the influence of technological parameters on the mechanical properties of tiles

Data from 15 experiments were analyzed to evaluate the influence of technological factors such as mixing temperature, mixing time, and pressure on the properties of tiles. The ANOVA results for compressive strength, flexural strength, and surface abrasion resistance were conducted with a confidence level of 95% and a significance level of 5%, as presented in **Table 7**.

Table 7. Analysis of variance results for compressive strength, flexural strength, and surface abrasion resistance.

Source	Compressive strength		Flexural strength		Surface abrasion resistance	
	F-value	p-value	F-value	p-value	F-value	p-value
Model	687.53	< 0.0001	489.08	< 0.0001	541.07	< 0.0001
A-Mixing temperature	1095.37	< 0.0001	148.41	< 0.0001	22.50	0.0051
B- Mixing time	253.74	< 0.0001	80.04	0.0003	1440.00	< 0.0001
C-Pressure	1330.82	< 0.0001	1321.78	< 0.0001	302.50	< 0.0001
AB	76.63	0.0003	140.29	< 0.0001	0.0000	1.0000
AC	589.43	< 0.0001	7.25	0.0432	245.00	< 0.0001
BC	31.39	0.0025	88.77	0.0002	20.00	0.0066
A^2	546.71	< 0.0001	18.21	0.0080	28.85	0.0030
B^2	127.02	< 0.0001	512.12	< 0.0001	1108.85	< 0.0001
C^2	2385.16	< 0.0001	2252.32	< 0.0001	1939.62	< 0.0001
R^2	0.9992		0.9989		0.9990	
Adjusted R^2	0.9977		0.9968		0.9971	
Adeq Precision	91.0262		62.3115		70.5193	

The model analysis in **Table 7** demonstrated that this model was fully consistent with the experiments, as evidenced by the model's Fisher statistics (Fisher) values of 687.53 for compressive strength, 489.08 for flexural strength, and 541.07 for surface abrasion resistance. The reliability of the model was evaluated with a 95% confidence interval. Process parameters with P values less than 0.05 indicate their significance to the mechanical properties in the design space. For compressive strength, the variables A (mixing temperature), B (mixing time), C (pressure), AB, BC, AC, A^2, B^2, and C^2 were all significant model terms with $p < 0.05$. Similarly, for flexural strength, the variables A, B, C, AB, BC, AC, A^2, B^2, and C^2 were significant, demonstrating their critical role in the manufacturing process of tiles made from recycled plastic and waste incineration ash. For surface abrasion resistance, the variables A, B, C, BC, AC, A^2, B^2, and C^2 were found to be significant, indicating their influence on the surface durability of the tiles. These results underscore the importance of optimizing these parameters to achieve the desired mechanical properties in the final product. The LoF (Lack of Fit) was used to assess data variation in the model. The LoF values for compressive strength, flexural strength, and surface abrasion resistance models are 0.0031, 0.0006, and 0.00000008, respectively, indicating that the model reflects data variation well.

After removing non-significant variables ($p > 0.05$) and applying regression analysis, the objective function of the model was determined, represented by the quadratic regression equation as follows:

Compressive strength = 18,25 + 0,50125A + 0,24125B + 0,5525C – 0,1875AB – 0,52AC – 0,12BC – 0,52125A2 – 0,25125B2 – 1,08875C2 (1)

Flexural strength = 10,10 + 0,08A + 0,05875B + 0,23875C - 0,11AB – 0,025AC + 0,0875*BC – 0,04125A2 – 0,21875B2 – 0,45875C2 (2)

Surface abrasion resistance = 0,02 + 0,000375A – 0,003B – 0,001375C + 0,00175AC + 0,0005BC – 0,000625A2 – 0,003875B2 – 0,005125C2 (3)

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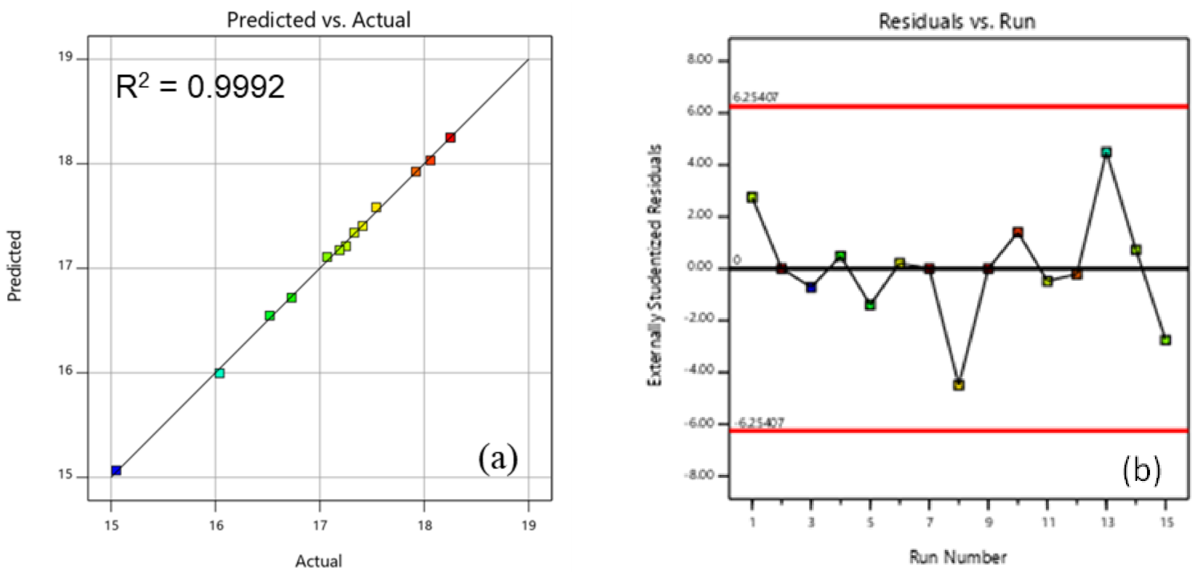
The positive and negative coefficients preceding the variables in the equation represent the positive and negative influences of different factors on all reactions. From regression equations (1) and (2), all three factors A, B, C positively influence compressive strength and flexural strength. The extent of their influence decreases in the order of C > A > B, corresponding to their coefficients in equations (1) and (2). .Equation (3) showed that factor A (mixing temperature) had a positive influence on surface abrasion resistance, meaning that as the mixing temperature increases, the surface abrasion resistance improves. This implies that higher temperatures help in creating a more durable surface for the tiles. On the other hand, factors B (mixing time) and C (pressure) had negative influences on surface abrasion resistance. This means that as the mixing time and pressure increase, the surface abrasion resistance decreases. Longer mixing times can lead to over-processing, causing the materials to become less cohesive and more prone to wear. Similarly, higher pressure can cause unwanted deformations or structural damage, reducing the material's ability to resist abrasion. Thus, while an increase in mixing temperature can enhance surface durability, excessive mixing time and pressure can have detrimental effects, underscoring the importance of optimizing these parameters to achieve the best mechanical properties for the tiles.

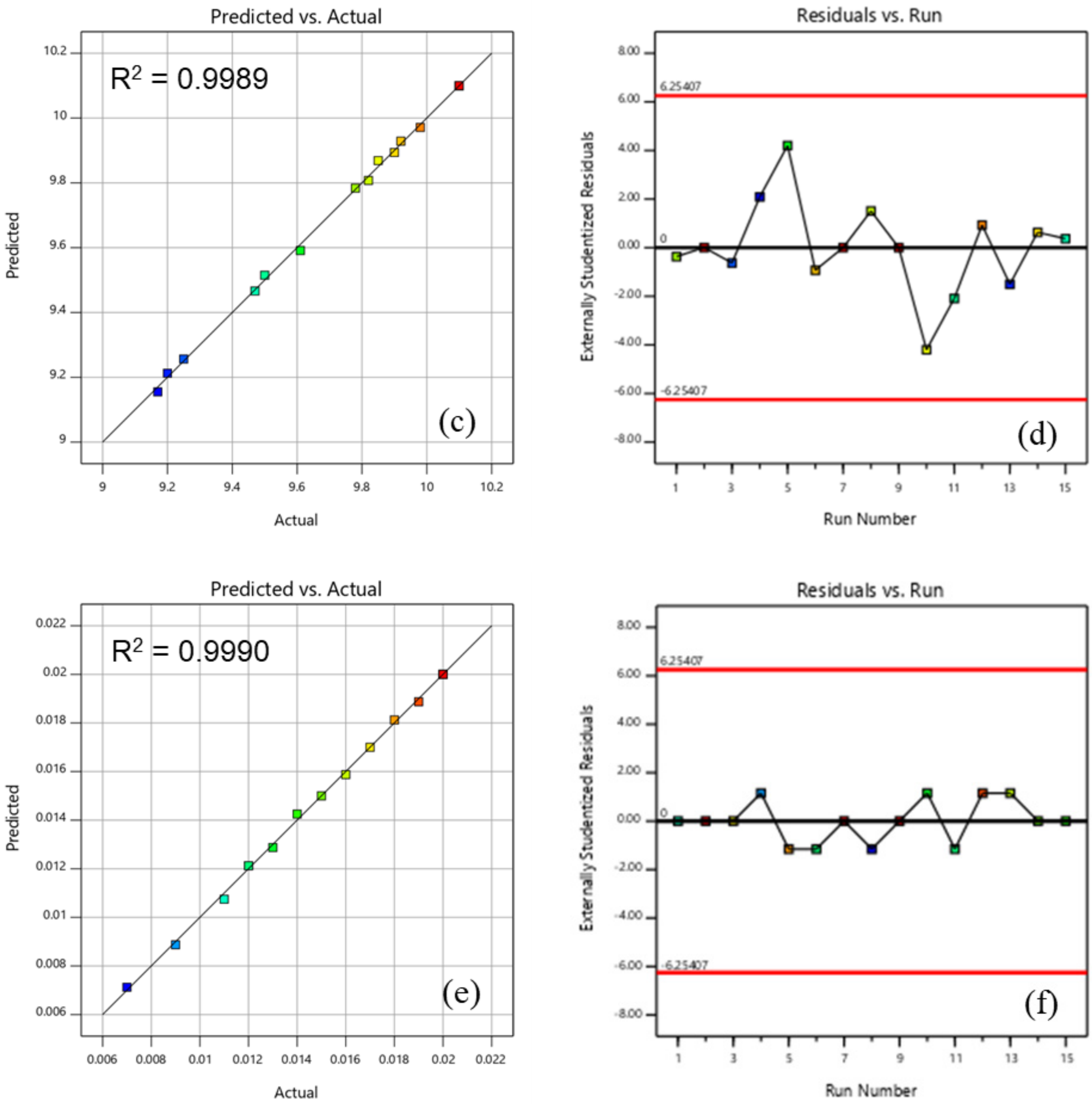
Analysis of diagnostic plots regarding predicted and actual responses

Diagnostic plots of predicted values versus actual values are an important step in experimental design and data analysis. The purpose of these plots is to assess the goodness-of-fit of the model by comparing the predicted values from regression equations with the actual experimental data. This helps identify any systematic biases or patterns that may indicate issues with the model. By visualizing the residuals (the differences between predicted and actual values), researchers can examine the normality, homoscedasticity, and independence of the residuals. These plots also help detect outliers or influential data points that may skew the results. Overall, diagnostic plots are essential for confirming the accuracy and reliability of the model, ensuring that the predictions align well with the observed data. The reaction plots generated by the model's diagnostic plots were presented in **Figures 2a – 2f**.

The residuals were randomly distributed along the mean line, indicating that the errors follow a normal distribution. This reflected a high degree of similarity between the model and the data [31]. **Figures 2a, 2c**, and **2e** showed a good correlation between experimental and theoretical values, as the experimental points cluster along the diagonal and the distribution of experimental points was random within the range (-8, 8) in **Figures 2b, 2d**, and **2f**. The model's adequacy was also confirmed by the determination coefficients R^2. The determination coefficient for compressive strength model, flexural strength model, and surface abrasion resistance model was 0.992, 0.9989, and 0.9990, respectively. This confirmed a strong relationship between the models and experimental data.

Figure 2. Normal probability plot of residuals for compressive strength (2a, 2b), flexural strength (2c, 2d), and surface abrasion resistance (2e, 2f).





Analysis of the influence of technological parameters on the mechanical properties of tiles

The influence of pairs of technological factors (AB, AC, BC) on the objective functions was depicted through 2D and 3D response surface plots of the tile manufacturing process (**Figures 3a-3f**). The independent variables were plotted on the X and Y axes, while the response was plotted on the Z axis. The color of the contour lines describes the levels of response, with blue, light green, and dark red indicating areas of less effective, intermediate, and effective interaction, respectively [24, 25].

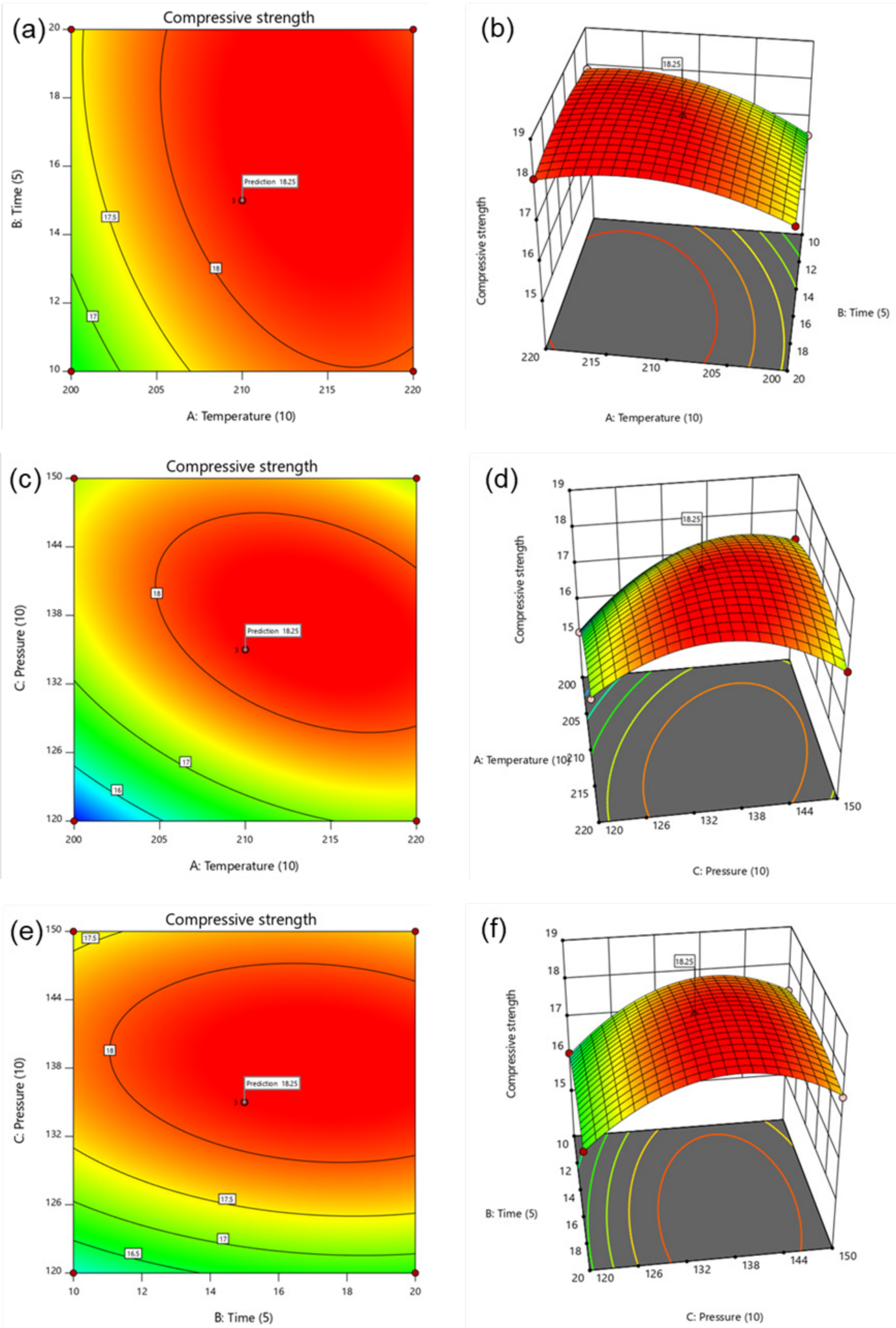
Analysis of the influence of technological parameters on compressive strength

Figure 3 indicated the influence of the interaction between mixing temperature, mixing time, and compression force on the compressive strength of tiles using 2D and 3D surface response diagrams.

Figures 3a, 3b illustrated the influence of mixing temperature and mixing time on the compressive strength of tiles. Initially, as the mixing temperature and time increase, the compressive strength of the tiles tended to increase. However, if the mixing temperature was further increased to 220°C and the mixing time to 20 minutes, this value tended to decrease as the components of the recycled thermoplastic may degrade. In the interaction between temperature and compression force in **Figures 3c, 3d**, as the mixing temperature increases, the initial compression force also increases and then decreases. Because of the high temperature, the viscosity of the system was reduced. Therefore, it reduced the activity of the components in the system while the high compression force caused undesired deformation and structural damage to the tiles. The same trend was observed for the interaction between mixing time and compression force on the compressive strength of tiles (**Figure 3**

e, f). As the mixing time increases, the components in the mixture distributed more evenly. However, prolonged mixing time causes agglomeration of ash and slag in the system, reducing the homogeneity of the system. For the value of the compressive strength objective function, the interaction between pairs of factors affected the value of the objective function in the order AC > AB > BC.

Figure 3. Surface Response Diagrams 2D, 3D illustrates the influence of interaction between mixing temperature, mixing time, and compression force on the compressive strength of tiles.



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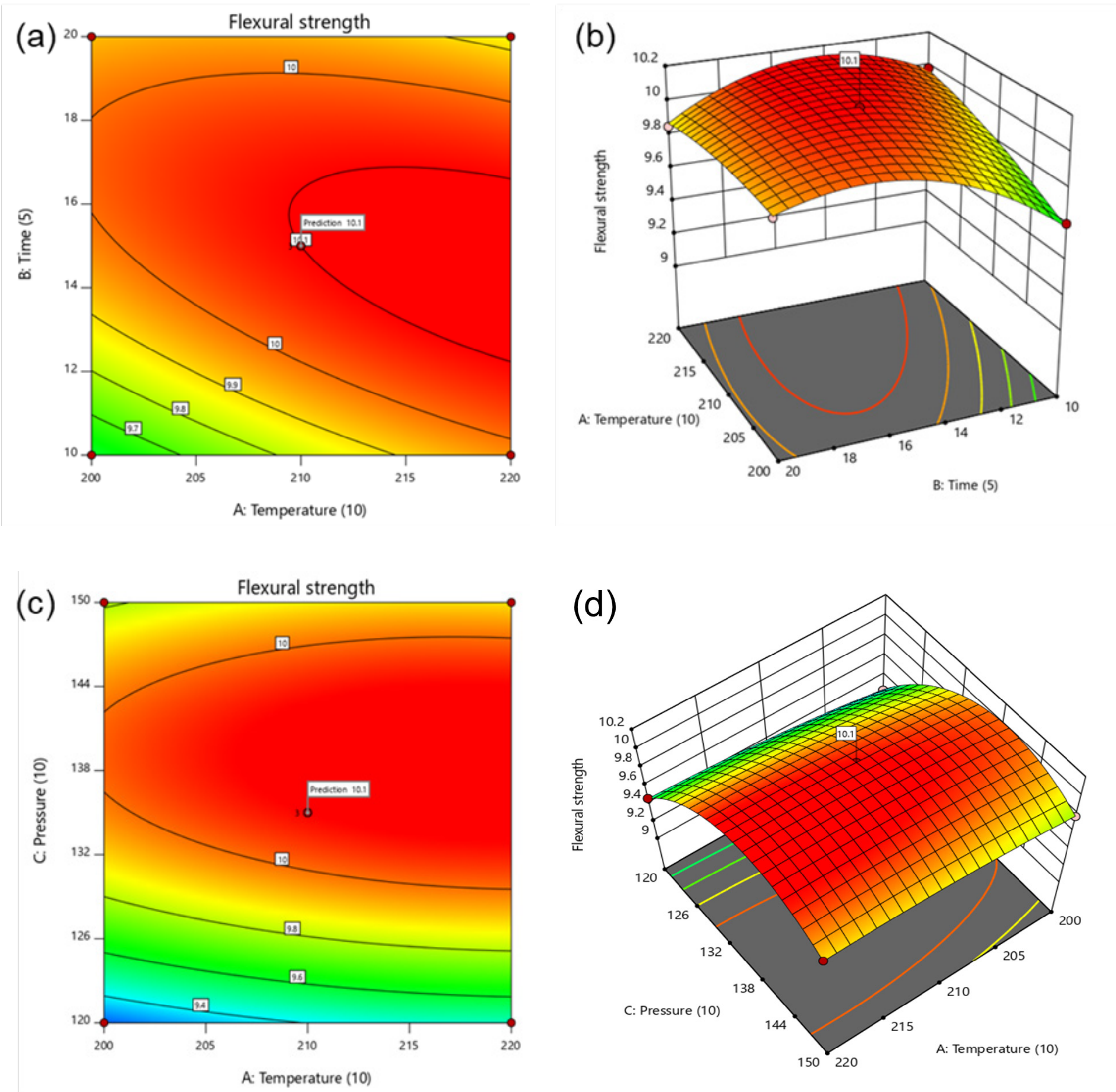
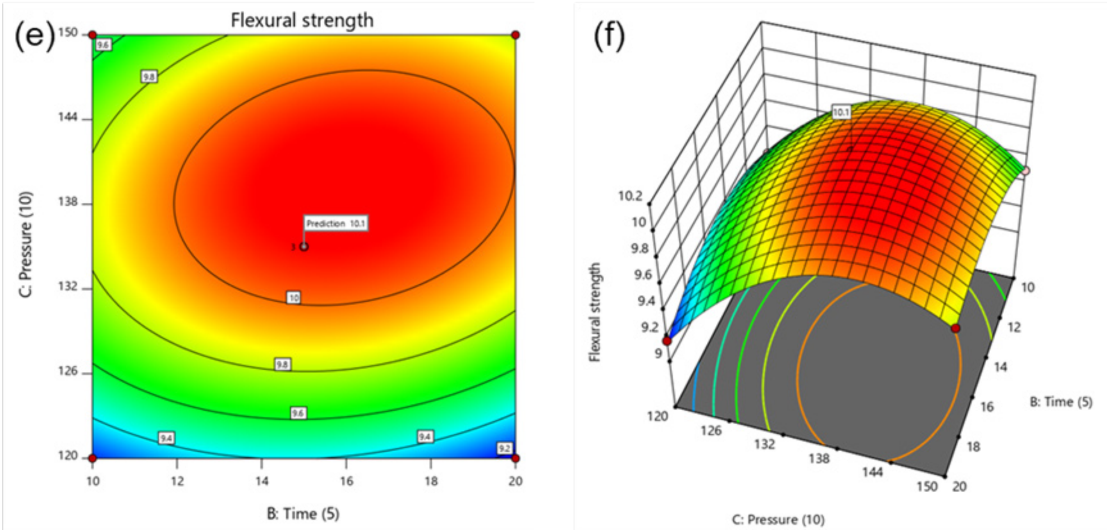
Analysis of the influence of technological parameters on flexural strength

The influence of the interaction between mixing temperature, mixing time, and compression force on the flexural strength of tiles is depicted by 2D and 3D surface response diagrams as presented in the **figure 4**.

Figures 4a, 4b show a trend of flexural strength as the temperature increases from 200°C to 210°C with mixing time under 15 minutes. However, flexural strength begins to decrease when the temperature and mixing time exceed these values simultaneously. Flexural strength is influenced by temperature and mixing time, as depicted in **Figures 4c, 4d**, and flexural strength affected by mixing time and compression force is presented in **Figures 4e, 4f**. From the 2D, 3D surface response diagrams, it can be observed that the maximum compressive strength is achieved under tile manufacturing conditions at a mixing temperature of 210°C, mixing time of 15 minutes, and compression force of 135 tons. For the value of the flexural strength objective function, the influence of interaction between pairs of factors on the value of the objective function decreases in the order AB > BC > AC.

Figure 4. Surface Response Diagrams 2D, 3D illustrates the influence of interaction between mixing temperature, mixing time, and compression force on the flexural strength of tiles.



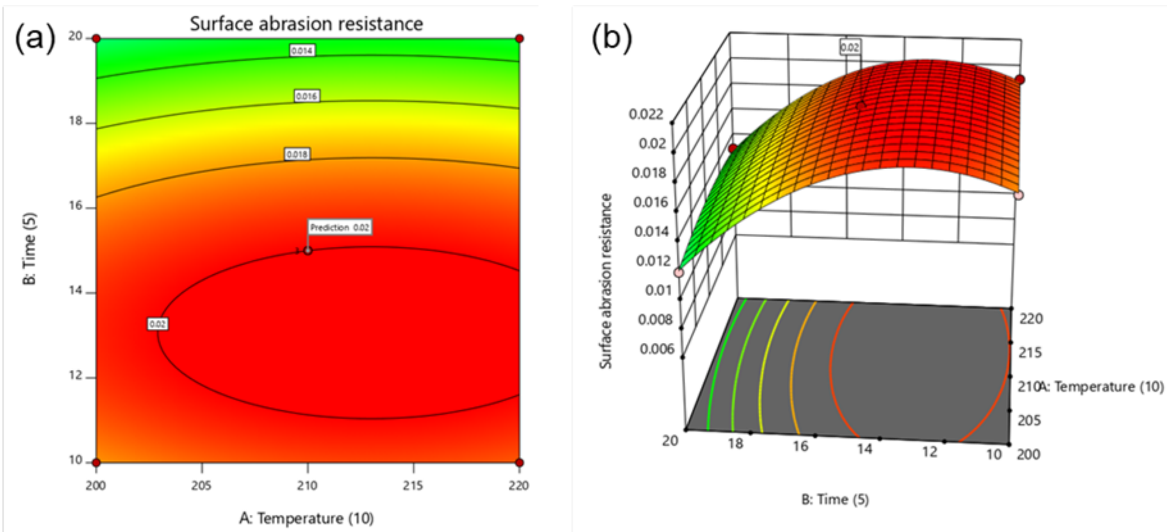


Analysis of the influence of technological parameters on surface wear resistance

The influence of the interaction between mixing temperature, mixing time, and compression force on the surface abrasion resistance of tiles is represented by 2D and 3D surface response diagrams as presented in the **figure 5**.

Plots in **Figure 5a and 5b** showed that initially, the surface abrasion resistance increased as the mixing temperature and time increase. However, this property decreased if the mixing time exceeds 15 minutes and the mixing temperature exceeds 210°C. The effects of the pairs of factors, temperature, mixing time, and mixing time with pressure, were presented in **Figure 5c, 5d**; and **Figure 5e, 5f**, respectively. For the surface abrasion resistance objective function, the influence of the interaction between pairs of factors on the objective function decreased in the order of AC > BC, and the AC factor pair did not affect this objective function.

Figure 5. 2D and 3D response surface plots illustrates the influence of the interaction between mixing temperature, mixing time, and pressure on the surface abrasion resistance of tiles.



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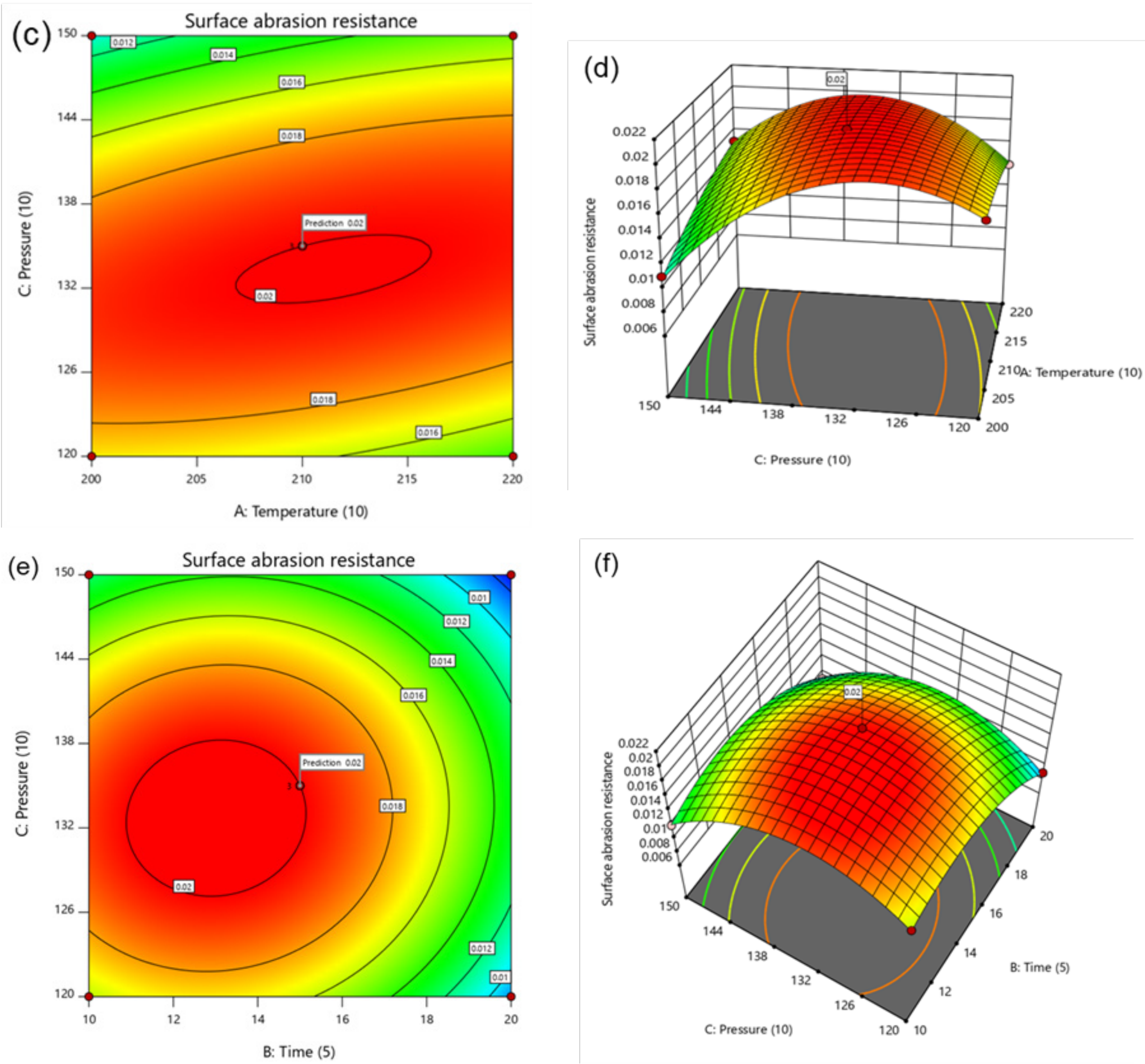

Optimization of the tile manufacturing process and verification

After conducting ANOVA analysis, some technical solutions were presented in Table 9. The optimal values of independent variables were determined by solving the quadratic equation using the objective function method presented in **Figure 6**. The chosen level of the objective function was level 2. The results of confirmation tests for the optimal tile manufacturing conditions were presented in **Table 8**.

Figure 6. Optimal conditions and predicted physical properties of tiles.

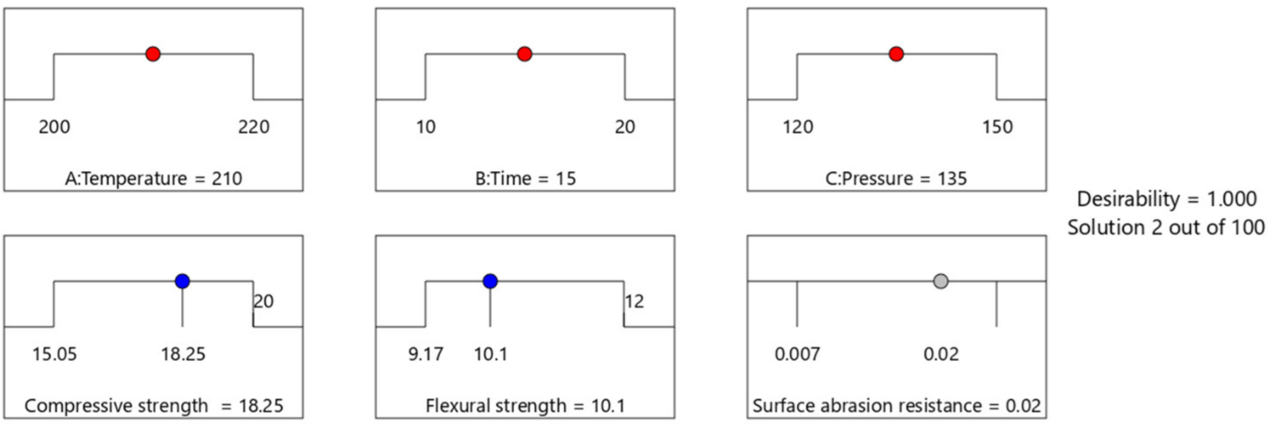

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Table 8. Confirmation test results with optimal tile manufacturing parameters.

Compressive strength (MPa)		Flexural strength (MPa)		Surface Abrasion resistance (J/cm2)		Error (%)		
Prediction	Experimental values	Prediction	Experimental values	Prediction	Experimental values	Compressive strength	Flexural strength	Surface Abrasion resistance
18.250	18.530	10.10	10.15	0.020	0.0207	1.53	1.48	3.50

Through confirmation experiments, the error between prediction and experimental values was < 5%. Therefore, the model can be effectively used to predict the mechanical properties of tiles. Tiles manufactured from recycled plastic and incinerator bottom ash have the highest compressive strength reaching 18.248 MPa [32], equivalent to the compressive strength of M150-grade tiles according to TCVN-1451:1998. The results of this study, along with technological advancements, not only allow the incorporation of recycled plastic combined with incinerator bottom ash into building material production [33] but also offer a beneficial and effective method to minimize its environmental impact compared to landfilling or incineration methods [34, 35]. Analysis of heavy metal content in tiles according to Vietnamese standards (QCVN 07) The composition of heavy metals in the studied samples was presented in **Table 9**.

Table 9. Heavy metal content in tiles

Content name	Unit	Sample 2		JIS A 5741:2016
		C1	C2	
Lead (Pb)	mg/L	< 0,00001	< 0,00001	≤ 0,01
Cadmium (Cd)		< 0,00001	< 0,00007	≤ 0,01
Mercury (Hg)		< 0,000261	< 0,00018	≤ 0,0005
Selenium (Se)		< 0,000032	< 0,00001	≤ 0,01
Arsenic (As)		< 0,00201	< 0,00098	≤ 0,01
Chromium (Cr)		< 0,00016	< 0,00234	≤ 0,05

Note: C^1: Concentration in blank sample; C^2: Concentration from test sample in leach solution

From Table 8, the heavy metals in both the initial tile samples and in the leach solution meet the standards and did not pose a health risk. Therefore, using the manufacturing process outlined from the ash, slag of the waste incineration plant and recycled thermoplastic can produce various other building materials such as interlocking tiles for public facilities like waste treatment plants, walls in parks, floor tiles, etc.

CONCLUSION

The influence of input parameters such as mixing temperature, mixing time, and compression force on the compressive strength, flexural strength, and surface abrasion resistance of tiles made from recycled thermoplastic and municipal incineration waste slag was analyzed. Variance analysis showed that the model is a statistically good predictor for these properties. Regression equations have been developed for compressive strength (1), flexural strength (2), and surface abrasion resistance (3) of the tiles. The model can effectively predict the mechanical properties of tiles manufactured from recycled thermoplastic and incinerated municipal waste slag. The optimal input parameters for manufacturing these tiles are a mixing temperature of 210°C, mixing time of 15 minutes, and compression force of 135 tons, resulting in compressive strength of 18.25 MPa, flexural strength of 10.10 MPa, and surface abrasion resistance of 0.02 J/cm2. The produced tiles meet the M150 grade according to TCVN-1451:1998 and comply with the physical properties, dimensions, and defects specified in TCVN 7744-2013 (exterior terrazzo tiles).

These findings demonstrate the effectiveness of optimizing the manufacturing parameters to produce high-quality paving bricks from recycled materials. The use of waste plastics and incineration ash not only provides a sustainable solution for waste management but also results in strong, durable construction materials. These bricks are suitable for various applications, including sidewalks, pathways, and other infrastructure projects requiring high load-bearing capacity and durability. This study highlights the potential for innovative recycling methods to contribute to environmental sustainability and material innovation in the construction industry.

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Data availability

The data used to support the findings of this study are included within the article.

Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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