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Identifying Effective Parameters for Ceramic Floor Tile Strength Using Design of Experiments Methodology

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ABSTRACT

The production of ceramic floor tiles requires experimentation to achieve acceptable quality and ensure the successful application of the final product. The strength of ceramic floor tiles depends on various parameters, some of which are controllable, while others are beyond the control of production processes. The design of experiments (DOE) is a cost-effective and efficient method for evaluating the production process through controllable variables. However, poorly designed experiments can lead to incorrect results, causing significant costs and waste. In this paper, we investigate the effects of pressure, firing temperature, and firing time on the strength and quality of ceramic floor tiles using the DOE methodology. The samples were tested for compressive strength following Iran's national standards. Optimal conditions were determined using a model and compared with results obtained from Minitab software. The final results show that the optimal compressive strength derived from Minitab's experimental design is 331 MPa, with parameters of 200 N pressure, 1120°C temperature, 48 minutes, and a 0.02 mesh size. In contrast, GAMS software produced an optimal compressive strength of 338 MPa under conditions of 200 N pressure, 1150°C temperature, 48 minutes, and 0.02 mesh size. The 8 MPa difference is attributed to rounding and the specialized analytical capabilities of both GAMS and Minitab.

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1. INTRODUCTION

Quality is a concept that has been important to humans since ancient times. Quality is a term that has different meanings and concepts. According to ISO (2005), it refers to the personal characteristics of products that meet customers' needs. The British Standards Organization (1991) defined product and service quality as the use of high-quality materials, high performance, and the highest reliability to meet customer satisfaction

and needs. Hatoush (1997) defines quality as a set of characteristics in products or services that meet specific requirements. Barrett (2000) observes that quality in manufacturing can satisfy a broad array of stakeholders. Additionally, Sanvido et al. (1992) emphasize that quality manufacturing projects, when successfully implemented, can lead to customer satisfaction and meet their expectations. Improving quality and efficiency is integral to the design cycle as well as to product and process development.

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Employing the design of experiments (DOE) method early in new product development cycles, as well as in improving existing products and optimizing manufacturing processes, is crucial for achieving product success. DOE, or Design of Experiments, has been recognized as a method for quality improvement since the late 19th century, gaining prominence as a competitive advantage in Japan and Western countries around 1990. DOE helps identify critical variables influencing product characteristics, systematically modifies controllable input parameters, and impacts the final product features. This statistical approach significantly reduces variations in quality characteristics and determines optimal levels for controllable variables to enhance process performance. Frequently employed in the preliminary stages of production as a quality control method, DOE is particularly valuable in industries like ceramic floor tile manufacturing, where achieving customer satisfaction and meeting specific needs are crucial. Thus, conducting foundational experiments is essential to ensure the quality and successful application of ceramic floor tile products.

The strength of ceramic floor tile products depends on several parameters, some of which are controllable and some of which are beyond production control. When the effectiveness of controllable variables on strength is measured, it can play an important role in improving the quality of ceramic floor tile end products and ultimately customer satisfaction. Overall, the main tile manufacturing process includes the following steps:

- Homogenization and grinding of primary materials
- Drying of slurries and production of granules
- Shaping by pressing
- Drying
- Application of slipware and glaze
- Printing of the pattern on the tile
- Firing of the products

In each production step, there are controllable variables that can affect the quality of the final product. In addition, there are various tests at the end that ensure product quality. Compressive strength testing is one of the tests that ensure the quality of the final product in this industry. In brittle materials, fracture occurs at maximum load, so tensile strength and breaking strength are combined. In very brittle materials, which include most ceramics, yield, tensile, and fracture stress are united. The bending test is an experiment in which a piece of ceramic (see Figure 1) is loaded at three points. The center shaft on the ceramic is a loading jaw, and the other two shafts on the sides are support bearings. In this test, the standard bending test is set at 300 for floor tiles and 115 for wall tiles.

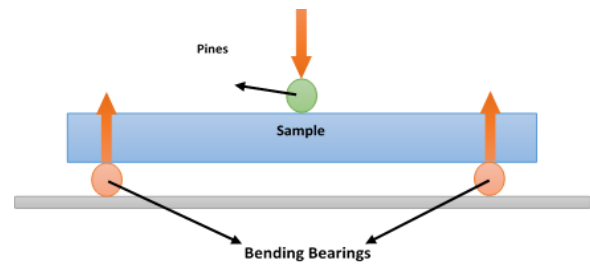


Figure 1. Bending test experiment

In the current article, we propose an innovative approach to examining the compressive strength of tiles in a new environment. This research utilizes a mathematical model tailored to this new environment and its corresponding parameters. Ultimately, the optimal value under the conditions of this new environment was obtained using GAMS software. The experimental design was also conducted using Minitab software, and its results were compared with the outcomes obtained from GAMS. The methodology employed in this research contributes to enhancing the accuracy and efficiency in evaluating the compressive strength of tiles in the studied environment.

The remainder of this paper is organized as follows: Section 2 provides a literature review of related studies. Section 3 outlines the objectives and assumptions of this study. Section 4 describes the research methodology. Section 5 presents the experimental results and discussion. Finally, Section 6 concludes the study.

2. Literature Review

Porcelain tiles are prepared from kaolin, silica sand, feldspar, clay raw materials, and various additives. Ceramic powders are calcined at different temperatures after grinding, drying, and sieving. After the powders are formed and dried, they are sintered at different temperatures. Firing shrinkage (FS), water absorption (WA), and three-point flexure tests of the samples are compared (Durgun & Abal, 2022). As mentioned earlier, the quality of the final tile and ceramic products is affected by controllable and non-controllable variables at different levels of manufacturing. Since the non-controllable variables are outside our scope of monitoring and control, we focus mainly on the controllable variables. Soil meshing is a measure used to sort soil grains. Soils are graded according to the obtained results from meshes or different sizes of their grains. Soil meshing is an important part of soil mechanics, especially in foundation engineering, because the size of soil grains explicitly affects the behavior and properties of soil, such as shear stress, compressibility, and permeability (Jordán et al., 2009). The powder used for the production of body cookies has a specific formula and consistent moisture content, which is obtained from the spray dryer and formed by the powder pressing process at defined pressures. Evaluations of the body properties

show that the powder sizes in the finished body and the amount of pressing pressure have a significant effect on the strength of the tile (ASTM, 2009). We describe that the powder particles displace and move during the formation of the tile body due to compressive forces, which are important parameters for the compressibility of the tile body. The increase in particle distribution in a cookie is accompanied by a decrease in porosity and is an important variable for increasing flexural strength. Hao (1999) studied the effect of hydraulic device pressure on the compressibility of the cookie body in the molding area and also the effect on the strength of the final product based on finite element analysis. Jiang Ing (2001) also described the effect of the compression area on the improvement of product quality based on the standards available in this industry. In the articles published in the field of pressing range, the standard pressure is set at a maximum of 250 bar (Crosock & Jung, 1982; Silva et al., 2014; Thiers et al., 2018).

In addition to the controllable variables mentioned above, there are others that can affect the quality of the final product. Ceramic parts have low strength after drying and can be crushed with a minimum of force or turned into clay by reabsorption of water and destruction. To increase the strength of the body, the parts must be fired. The firing of ceramics is done in a kiln, for which there are different models, but usually, a roller kiln is used because it has the necessary flexibility for short cycles, in which, due to the action of heat, clean particles combine and increase the strength of the part. When firing ceramic parts, each composition has specific run-out temperature ranges. Depending on the composition, the run-out temperature varies with the heat temperature. The following table shows the temperature ranges. The declared temperatures may differ for different compositions (Baccour et al., 2009; Edelson & Glaeser, 1986).

TABLE 1. Removed Compositions in different temperatures from tile biscuit

Carbonates, Sulfates, Crystallized water	Carbon and Organic Compositions	Humidity
Carbonates 400-1000 C	Some of Organic compositions Between 200-300 C	About 200 C
Sulfates Over than 1000 C	Carbon up to 1000 C	
Crystallized Water Over than 400 C		

Manfredini and Romagnoli (1999) presented a suitable temperature for baking brick cookies between 1050 and 1180 degrees Celsius. They also studied the existing compositions in clay and their effects on the flexural strength of bricks. Finally, they introduced clay with the appropriate number of compositions to produce bricks with suitable strength. Hamisi et al. (2014) studied

the effects of firing temperature on the physical properties of bricks and ceramics. They described a suitable temperature for baking tiles between 1100 and 1150 degrees Celsius, noting that all compositions that need to leave the cookie come out at this temperature. The duration of the baking cycle in the oven is another controllable variable in the manufacturing process of the tiles, which depends on the type of tiles. For example, the cycle for baking single-wall tiles is less than 50 minutes. From the studied articles, the importance of paying attention to the bottom grid, the correct pressure during pressing, the firing time in the kiln, and the temperature, which significantly impact the strength of the tiles and the final ceramic product, can be seen. We can use statistical methods to evaluate the influence of these parameters on bending strength, which are also used to improve the production process. One of the most important statistical methods is the DOE method. DOE is used to determine the relationships between the effective parameters of a process and its results. In the final analysis of the results of these experiments, the parameters that significantly impact the results are identified (Montgomery, 2017). In similar research, we can refer to the work of Hmisloğlu and Bayrak (2004), in which the flexural strength of concrete is improved by using the DOE.

Many studies have been conducted on the influence of different parameters on the resistance of floor tiles. For example, Meena et al. (2024) introduce innovative bamboo and marble dust ceramic systems, highlighting their superior qualities and significant impact on crystalline phase composition. By partially replacing marble powder with bamboo dust, it offers a novel approach to ceramic tile production, demonstrating promising results in terms of rupture modulus and meeting or exceeding specifications for water absorption, loss of ignition, tile strength, and linear shrinkage. Castillo et al. (2021) gathered informative insights into various variables influencing the compressive strength of floor ceramic tiles, such as temperature and baking time, type and concentration of alkaline activator, water content, and impurity effects. Tahiwa et al. (2023) evaluated the effect of high temperatures up to 800 degrees Celsius on the compressive strength of ceramics. Ercioglu Akdogan et al. (2023) contend that process control in tile baking is highly challenging, considering it the most crucial stage in ceramic production. In their research, they employ manufacturing technology and statistical methods together to produce low-cost, high-quality products at optimal baking temperatures and times. Eren Gültekin (2018) investigated the effects of heating rate and sintering temperature on the strength, shrinkage, and apparent density of ceramic tiles. In their study, experiments were designed as a 32-factor full factorial design, where the individual effects of the two main factors and their interaction were determined. The values of resistance, shrinkage intensity, and apparent

density were analyzed using MINITAB 17 statistical software. They concluded that the interaction effect of heating rate and sintering temperature influences strength, shrinkage, and apparent density, and as a main factor, the effect of sintering temperature is significant. [Ochen et al. \(2021\)](#) addressed the investigation of quartz particle size (larger than 45 micrometers) and its detrimental effects on the physical and mechanical properties of ceramic tiles. They believe this adverse effect is due to various factors, including the microstructure (pores) post-sintering. In their study, they examined the influence of quartz particle size (QPS) on the firing behavior and flexural strength of ceramic tiles made from raw materials. [Zamani et al. \(2023\)](#) conducted a study on the investigation and optimization of the composition and firing temperature of ceramic tiles using statistical analysis techniques. In their research, they employed a full factorial design, which included model adequacy assessment, analysis of variance, Pareto charts, interaction plots, regression modeling, and response surface optimization. Key factors included Seger ratios of SiO₂/Al₂O₃, Na₂O/K₂O, MgO/CaO, and firing temperature. Their research findings indicate that optimal properties, such as maximum strength, can be achieved with SiO₂/Al₂O₃ = 5.2, Na₂O/K₂O = 1.50, MgO/CaO = 3.0, and a firing temperature of 1180 degrees Celsius.

The response data were analyzed using ANOVA (analysis of variance) by the Taguchi method. According to the ANOVA table, the water and silicate vapor contents play an important role in the primary flexural strength. [Balak and Zakeri \(2016\)](#) also used DOE to improve the flexural strength of composites. They analyzed nine parameters, such as temperature, time, and pressure, in four stages using statistical analysis of variance. In the current article, we propose an innovative approach to examining the compressive strength of tiles in a new environment. This research utilizes a mathematical model tailored to this new environment and its corresponding parameters. Ultimately, the optimal value under the conditions of this new environment was obtained using Gams software. The experimental design was also conducted using Minitab software, and its results were compared with the outcomes obtained from Gams. The methodology employed in this research contributes to enhancing the accuracy and efficiency in evaluating the compressive strength of tiles in the studied environment.

3. Objectives and Assumptions

In this paper, we intend to study the compressive strength of ceramic floor tile products based on the effective parameters (amount of bottom mesh, suitable pressure during pressing, firing time, and temperature in the kiln) identified in previous research. Our goal is to select the best-optimized conditions. Using a two-step DOE approach, we will sort all the necessary tests and then evaluate the strength quality of the products with the

assistance of the strength testing laboratory. It is important to note that this laboratory operates within the quality control department of Birjand Niloufar Tile Company in collaboration with the factory. The quantities provided in Table 2 of the DOE align with all company restrictions and established standards for the ceramic tile industry.

TABLE 2. Effective Parameters range in research

Level	A	B	C	D
	Pressure (N)	Temp.(C)	Time (Min)	Mesh
(- 1) Low	200	1120	45	0.02
(+1) High	220	1150	48	0.04

4. Research Methodology

Quality improvement and industrial manufacturing efficiency are only effective when integrated into every part of the design and production cycle. The precise application of statistical methods like DOE can streamline production processes, enhance safety, and improve system functionality. Moreover, these methods allow for significant portions of product design, development, and related activities to be reusable, thus enhancing overall efficiency and innovation.

The DOE approach was utilized to analyze and model the process, incorporating full factorial designs, fractional designs, and central composite designs. Factorial designs investigate the impact of two or more variables on a response variable. When these variables in the factorial designs have two levels, the number of trials required is represented as 2k, where k is the number of variables. Full factorial designs establish a linear relationship between the independent variables and the response variables. As the number of independent variables increases, the number of experiments required for full factorial designs also increases.

As mentioned earlier, four effective independent variables for the strength of ceramic floor tile products were identified and used in this article: floor mesh, appropriate pressure during pressing, baking time, and temperature in the oven. To study the effects of the identified parameters, the experiment must be conducted randomly. These experiments were conducted using a four-factorial design with four factors: suitable pressure during pressing (A), baking temperature in the oven (B), baking time in the oven (C), and amount of bottom mesh (D), each at two levels with two iterations. The high level (the highest amount for a factor, considering the constraints available in the company) and the low level (the lowest amount for each factor, considering the constraints available in the company) for each variable are shown in Table 2. After configuring the samples for the strength experiment, a product sample is prepared according to the specified amounts for the variables, and the flexural strength is tested. The results are presented in Table 3.

TABLE 3. Tile strength in exchange for different levels of study

10	pattern	Independent Variables				Response Variable	
		A	B	C	D	R1	R2
1	1	-1	-1	-1	-1	278	287
2	A	1	-1	-1	-1	224	245
3	B	-1	1	-1	-1	343	318
4	AB	1	1	-1	-1	245	253
5	C	-1	-1	1	-1	328	334
6	AC	1	-1	1	-1	290	267
7	BC	-1	1	1	-1	276	243
8	ABC	1	1	1	-1	232	254
9	D	-1	-1	-1	1	340	302
10	AD	1	-1	-1	1	220	290
11	BD	-1	1	-1	1	280	298
12	BAD	1	1	-1	1	330	266
13	CD	-1	-1	1	1	356	300
14	ACD	1	-1	1	1	296	265
15	BCD	-1	1	1	1	178	232
16	ABCD	1	1	1	1	234	289

The overall approach to statistical analysis 2k includes the following:

1. Evaluation of factor effects, resistance and variable index
2. Running the primary model
3. Statistical test
4. Running the final model
5. Analysis of the residuals
6. Analysis of the results

5. Experimental Results

5.1. Evaluation of factor effects, resistance and variable index

Table 4 shows the results of these evaluations. The coded variable indices were used to estimate the indices of the regression model. Table 4 presents the primary number of the model:

$$\begin{aligned}
 Resp = & 277.90 - 15.41A - 10.97B + 11.34AB - 4.53C + \\
 & 7.91AC - 20.16BC + 6.16ABC + 1.84D - 7.09AD - \\
 & 5.41BD + 24.97ABD - 0.34CD + 0.34ACD + 1.03BCD - \\
 & 2.53ABCD
 \end{aligned}$$

TABLE 4. Table of Resistance and Effect

Patterns	Independent Variables														
	ABCD	BCD	ACD	CD	ABD	BD	AD	D	ABC	BC	AC	C	AB	B	A
1	+	-	-	+	-	+	+	-	-	+	+	-	+	-	-
A	-	-	+	+	+	+	-	-	+	+	-	-	-	-	+
B	-	+	-	+	+	-	+	-	+	-	+	-	-	+	-
AB	+	+	+	+	-	-	-	-	-	-	-	-	+	+	+
C	-	+	+	-	-	+	+	-	+	-	+	+	+	-	-
AC	+	+	-	-	+	+	-	-	-	-	+	+	-	-	+
BC	+	-	+	-	+	-	+	-	-	+	-	+	-	+	-
ABC	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+
D	-	+	+	-	+	-	-	+	-	+	+	-	+	-	-
AD	+	+	-	-	-	-	+	+	+	+	-	-	-	-	+
BD	+	-	+	-	-	+	-	+	+	-	+	-	-	+	-
BAD	-	-	-	-	+	+	+	+	-	-	-	-	+	+	+
CD	+	-	-	+	+	-	-	+	+	-	-	+	+	-	-
ACD	-	-	+	+	-	-	+	+	-	-	+	+	-	-	+
BCD	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
ABCD	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Resistance	-81	33	11	-11	799	-173	-227	59	197	-645	253	-145	363	-351	-493
Effect	-5.06	2.06	0.69	-0.69	49.94	-10.81	-14.19	3.69	12.31	-40.31	15.81	-9.06	22.69	-21.94	-30.81
Variable Index	-2.53	1.03	0.34	-0.34	24.97	-5.41	-7.09	1.84	6.16	-20.16	7.91	-4.53	11.34	-10.97	-15.41

5.2. Statistical test

The analysis of variance can be found in Table 4. In this table, the magnitude of the F-value and the p-value can be used to comment on the effectiveness of the factors on the response variables. Since the experiments

were conducted with an error level of 0.05, all factors with a p-value less than 0.05 are considered effective in our model. Moreover, according to the table. Moreover, according to the table, $F_{0.05,1,16} = 4.49$, the factors with f-values above 4.49 have an effect.

TABLE 5. Variance analysis related to a case study in tile industry

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	41785.2	2785.7	3.69	0.007
Linear	4	12211.1	3052.8	4.04	0.019
press	1	7595.3	7595.3	10.06	0.006
temp	1	3850.0	3850.0	5.10	0.038
time	1	657.0	657.0	0.87	0.365
mesh	1	108.8	108.8	0.14	0.709
2-Way Interactions	6	24224.4	4037.4	5.35	0.003
press*temp	1	4117.8	4117.8	5.46	0.033
press*time	1	2000.3	2000.3	2.65	0.123
press*mesh	1	2831.3	2831.3	3.75	0.071
temp*time	1	13000.8	13000.8	17.23	0.001
temp*mesh	1	935.3	935.3	1.24	0.282
time*mesh	1	1339.0	1339.0	1.77	0.202
3-Way Interactions	4	5144.6	1286.2	1.70	0.198
press*temp*time	1	1212.8	1212.8	1.61	0.223
press*temp*mesh	1	3894.0	3894.0	5.16	0.037
press*time*mesh	1	3.8	3.8	0.01	0.944
temp*time*mesh	1	34.0	34.0	0.05	0.835
4-Way Interactions	1	205.0	205.0	0.27	0.609
press*temp*time*mesh	1	205.0	205.0	0.27	0.609
Error	16	12075.5	754.7		
Total	31	53860.7			

To identify effective factors in the response variables, factorial effects and reciprocal effects diagrams can also be used (Figures 2 and 3, respectively). In Figure 2, the slope of each factor indicates the intensity of its effect on the response variable. Thus, we conclude that the effects of factors A and B (pressure and temperature) are stronger than those of factors C and D (time and mesh size). Moreover, a positive slope indicates a direct effect on the response variable, while a negative slope indicates an inverse effect.

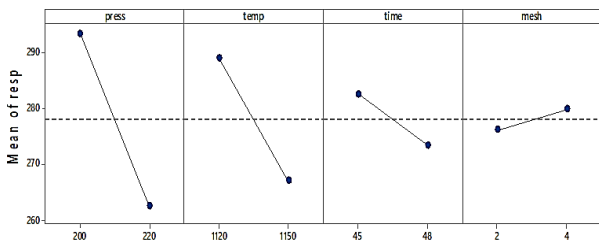


Figure 2. Factorial Effects

Figure 3 shows the reciprocal effects of the factors. In this figure, changes in the factors lead to the intersection of their responses. We can assert that the simultaneous change in the factors is effective; however, to determine the level at which the two factors influence the response variables, we need to utilize contour plots, as illustrated in Figures 4 and 5.

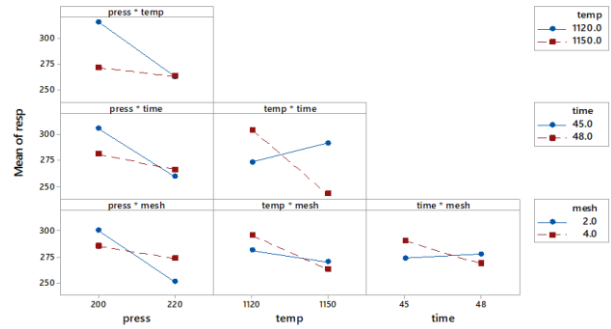


Figure 3. Interaction effects

Figure 4 illustrates the dual effects considering the low level of the independent variables, while Figure 5 depicts the dual effects at the high level of the other variables. The bold areas in each graph indicate the largest effect of these variables on the response variable analyzed below.

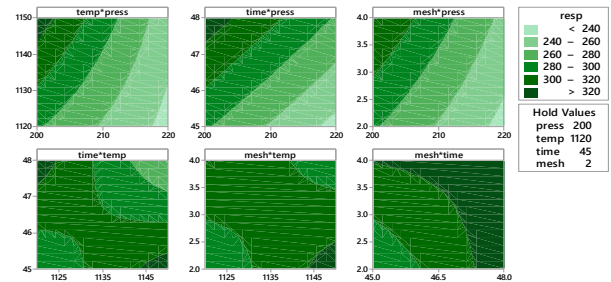


Figure 4. Counter diagram at low level of the variable

TABLE 6. Most response domains in dual effects exchange considering a low level of other independent variables

	Press (N)	Temp (C)	Time (Min)	Mesh
Up- Left side	200	1150	45	2
Up- Center	200	1120	48	2
Up-Right	200	1120	45	2
Down-left (two levels)	200	1120	48	2
	200	1150	45	2
Down-Center	200	1150	48	2
Down- Right	200	1120	48	4,2

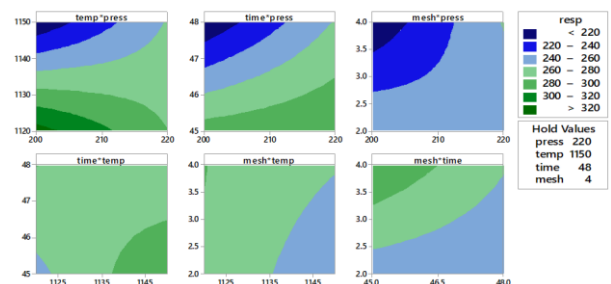


Figure 5. Counter diagram in high levels of variables

TABLE 7. Maximum response surface in dual effects exchange considering a high level of other independent variables

	Press (N)	Temp (C)	Time (Min)	Mesh
Up-Left	200	1120	48	4
Up-Center	In other diagrams there are not bold green (Maximum response area)			
Up-Right				
Down-Left				
Down-Center				
Down- Right				

In Figure 5, only the upper left diagram contains the largest range for the response variables (bold green area), while the other diagrams do not. From these graphs, we can observe the effects of the various factors on the response surface, but we cannot infer the most effective factors. For this purpose, we will use Pareto and normal diagrams, as shown in Figures 6 and 7.

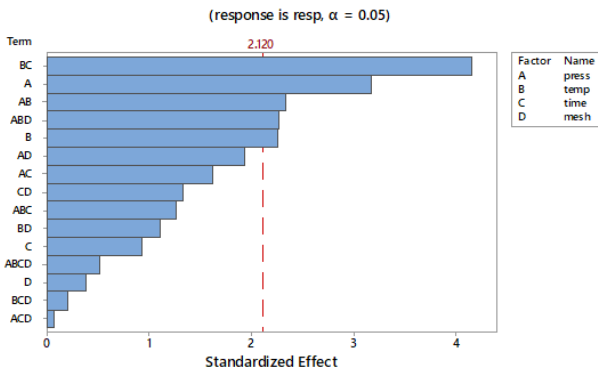


Figure 6. Pareto diagram

According to the Pareto diagram and the influence limit of the response variables (2.120), the effective factors are determined. This is also evident from the normalized diagram in Figure 9. It is important to note that the greater the distance between the 16 individual effects and the reciprocal elements in Table 2 and the normalized line, the greater the effect of the respective factor on the response variable.

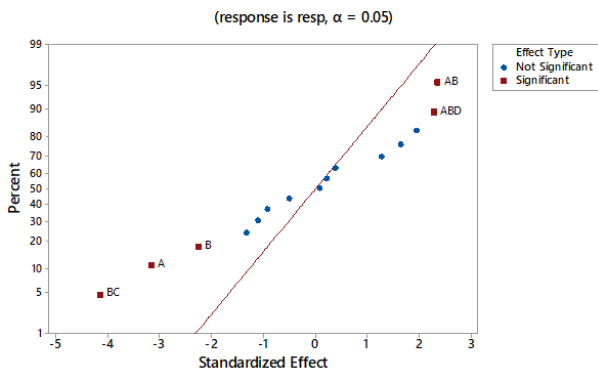


Figure 7. Normalized diagram

The Pareto charts and the normalized charts show the results of the variance table. Therefore, we can refer to

the table at the beginning and observe which parameters affect the analysis of variance.

5.3. Model correction (Final model)

The primary model was redesigned according to the previous conclusions as follows:

$$RESP = 277.90 - 15.41(PRESS) - 10.97(TEMP) - 20.16(TEMP)(TIME) + 11.34(PRESS)(TEMP) + 24.97(PRESS)(TEMP)(MESH)$$

5.4. Residual analysis

After defining the regression model, estimate the different quantities from the experiments using this model and calculate the difference between the actual quantities and the predicted quantities. Before accepting the results of the analysis of variance and finalizing the model, check the residuals of this experiment (the difference between actual and predicted quantities) to determine if they are normal and random, ensuring valid results. Figures 8 and 9 show the normal plot of residuals (clustered around the line) and the plot validating random observations, respectively.

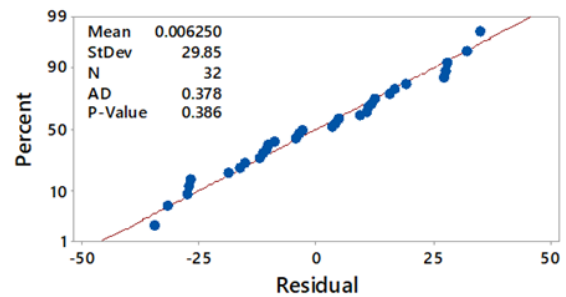


Figure 8. Randomness validation of the amount of residuals

Based on Figure 8, the p-value is validated to be normal (greater than 0.05).

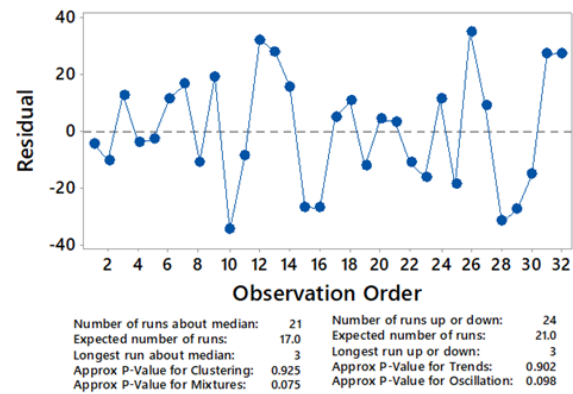


Figure 9. Normal validation test of residuals

Based on Figure 9, the p-values confirm randomness (each of the four elements is greater than 0.05). The competency evaluation of the model shows that the residual analysis of this model is satisfactory.

5.5. Analysis of results

To obtain the optimal answer, the Gams and Minitab software are used with the results compared.

5.5.1. Analysis with GAMS software

To obtain the optimized answer, the following model is used:

$$\begin{aligned} \text{Max resp: } & 277.90 - 15.41 * x_1 - 10.97 * x_2 - \\ & 20.16 * x_2 * x_3 + 11.34 * x_1 * x_2 + 24.97 * x_1 * \\ & x_2 * x_4 \\ -1 \leq x_1 \leq & +1 \\ -1 \leq x_2 \leq & +1 \\ -1 \leq x_3 \leq & +1 \\ -1 \leq x_4 \leq & +1 \end{aligned}$$

The optimized answer in the software GAMS can be found below:

TABLE 8. The optimized answer of the proposed model

resp	A	B	C	D
338.81	-1	1	1	-1

The coded variables are converted to decoded variables at the end, given below:

TABLE 9. The converted variables

resp	A	B	C	D
338.81	200	1150	48	0.02

The following figure shows the subtitle of the final answer in the GAMS software.

TABLE 10. Optimized answer in Gams Software

34 Variable Z.L				338.810			
34 Variable X.L							
1	-1.000	2	1.000	3	1.000	4	-1.000

5.5.2. Analysis with Minitab software

According to the results from Minitab software, the optimized set of response variables is also 331, which aligns with the sets of Mesh = 2, Time = 48, Temperature = 1120, and Pressure = 200.

TABLE 11. Results from Minitab software

Solution	Goal	press	temp	time	mesh	Resp Fit	Composite Desirability
1	Maximum	200	1120	48	2	331	0.839744

6. Conclusion

One of the competitive advantages in the ceramic tile industry is the emphasis on the final quality of ceramic floor tiles, particularly their compressive strength. To enhance this attribute, numerous controllable variables can be manipulated. The DOE approach is particularly well-suited for studying these specific variables. This

study aimed to investigate the quality of ceramic floor tile products by identifying several critical and influential factors: the amount of floor mesh, the appropriate pressure during pressing, firing time, and kiln temperature. These variables were tested using experimental designs and factorial patterns at two levels—high and low. The optimized conditions for the independent variables were determined using the created model, with results analyzed through Minitab software and compared to those obtained from the model. Notably, the 8-unit difference between the optimized values from Minitab and those from GAMS is attributed to rounding when configuring the model for use in GAMS. The final results reveal that the optimal compressive strength achieved through the experimental design, as calculated in Minitab, is 331 megapascals. This result was obtained under the following conditions: a pressure of 200 newtons, a temperature of 1120 degrees Celsius, a duration of 48 minutes, and a mesh size of 0.02. Conversely, the mathematical model solved in GAMS suggests an optimal compressive strength of 338 megapascals, achieved with identical parameters except for a higher temperature of 1150 degrees Celsius. The discrepancy of 8 units between the results from GAMS and Minitab is due to the rounding of numbers in the GAMS model, whereas Minitab offers more specialized capabilities in analyzing and retrieving optimal solutions in experimental design.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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