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Research Article

Designing Hollow Brick Waste Based Alkali Activated Composites by Taguchi Method

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ABSTRACT

The use of waste materials in alkali-activated material technologies is important in terms of sustainability. The production of alkali-activated composites (AAC) with hollow brick waste (HBW) as a binder may contribute to solving existing environmental problems related to the depletion of natural resources. In this study, mortars were produced using different concentrations (6 M, 8 M, and 10 M NaOH) and Alkaline Activator/Powder Material (AA/PM) ratios of 0.30, 0.35, and 0.40 through the alkali activation method. The hollow brick waste (HBW) powder was obtained by grinding inactive bricks in brick factories. The prepared mortars were cured separately for each mixture at 90°C for 24 hours. Compressive and flexural strength tests were performed on the prepared perforated hollow brick waste-based composites. The Taguchi method was used to determine the optimum mixing ratios by conducting compressive and flexural strength tests on the produced AAC. To optimize the parameters determined using the Taguchi method, the best mixing ratios were determined using the L9 (3^2) orthogonal index. The compressive and flexural strengths of the mixtures were evaluated considering the signal to noise ratio "larger the better" and the highest compressive strength value was 63.669 MPa and the highest flexural strength value was 6.629 MPa according to the optimum values. According to the obtained results, it was determined that the AAC produced at 6 M NaOH and 0.30 AA/PM ratio exhibited the highest compressive and flexural strength values.

1. Introduction

The most widely used engineering material in the world is concrete. Cement, on the other hand, is the most costly, least environmentally friendly, and energy-intensive material of traditional concrete, despite being suitable and readily available for construction applications [1]. The cement industry accounts for 5-8% of human-induced CO_2 emissions, resulting in significant carbon emissions [2]. In terms of sustainability and environmental awareness, the design, production, and use of eco-friendly building materials that will contribute to reducing the use of cement-based materials by using recycled or waste materials to minimize energy and natural resource consumption has become a topic of interest [3]. Therefore, in recent years, there has been an increased interest in alternative studies aiming to produce building materials without using cement. The fact that alkali-activated composite materials produced using industrial waste products and/or recycled products have much lower CO_2 emissions compared to Portland cement has become an important issue in materials science [4-7]. Therefore, the production of alkali-activated materials has contributed to both the reduction of carbon dioxide emissions and the development of sustainable building materials with adequate mechanical parameters [8-10].

With the increase in urbanization, significant amounts of waste are generated each year as a result of infrastructure improvement, repair and demolition [11]. The waste generated after

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construction and demolition activities has become a major problem for society [12]. Therefore, the use of construction and demolition waste in various construction processes is being encouraged in specific locations around the world. Construction and demolition waste is used in concrete production as recycled coarse and fine aggregates according to their sizes [13, 14]. Recycled coarse aggregates are currently applied in the production of non-structural concrete and sub-base foundations [15].

Numerous studies have shown that concrete can be produced by binding materials such as fly ash and blast furnace slag, which contain alumina and silica, with alkali activators without the use of cement [16, 17]. As a result of the activation of fly ash and blast furnace slag with alkalis, calcium silicate hydrate (C-S-H) structures similar to cement-based binders are formed [18]. When the properties and performance of cement-free and alkali-activated fly ash or blast furnace slag binders are evaluated, it has been revealed that they can be used as an alternative to cement through research studies [19]. In this regard, studies on the use of various agricultural and industrial wastes as well as construction and demolition wastes activated with alkali activators have increased when environmental problems and factors such as the decrease of natural resources are taken into account [20, 21]. The production of alkali-activated composites involves the utilization of waste materials, contributing to recycling and the production of sustainable and environmentally friendly building materials [22-24].

The results obtained in the study where recycled fine powder was used as a partial replacement of fly ash at different substitution rates (10%, 20%, 30%, 40% and 50%) as a partial replacement of fly ash showed that the replacement of recycled fine powder up to 30% improved the strength and durability properties of geopolymer mortar mixtures [25]. In the study investigating the effect of activator type, usage rates and combinations on the rheological and workability performance of CDW-based geopolymer matrix, wall and roof elements containing recycled aggregates such as brick, glass waste, tile and concrete waste were prepared and it was recommended that the activator selection should be made according to the application needs [26].

In the study conducted by Yurt (2020), alkali-activated concrete (AAC) samples produced using ground granulated blast furnace slag (GGBFS) were tested for capillary water absorption, density, Dynamic Elasticity Modulus (DMoE), compressive strength, tensile strength in splitting, wear resistance tests and microstructure analyzes. The study determined that GGBFS can be used entirely in AAC production, and high-strength cement-free concrete with a compressive strength of 82.32 MPa was achieved [27]. In the study conducted by Yıldırım et al. (2021), as different wall units, red clay brick, hollow brick and tile were used in binary combinations with a total weight of binder in 75-25%, 50-50% and 25-75% ratios. According to the results obtained from the study, it was observed that alkali-activated binders with compressive strength up to 80 MPa can be produced [28].

In a study examining the strength and wear properties of geopolymer concrete prepared with zeolite-incorporated high-temperature furnace slag at weight percentages of 5%, 10%, and 15% over time, it was stated that the highest compressive strength value of 88 MPa was obtained at 60 °C water curing [29]. It was observed that the increase in the amount of zeolite added to geopolymer concrete resulted in an increase in wear resistance. In the study where recycled clay brick, recycled ceramic wall tile and recycled concrete wastes were used, the relationship between fresh and mechanical properties such as fluidity, setting time, compressive strength and microstructure and design factors were comprehensively investigated. According to the results obtained, it was confirmed that recycled clay brick, recycled concrete wastes and recycled ceramic wall triple combinations significantly increased the sustainability of geopolymer binders compared to their individual use [30].

Alkali-activated mortar specimens were produced by adding different ratios (5%, 10% and 15%) of marble powder and 0.5% of glass fiber to ferrochrome slag ground to the same fineness as cement. Compressive strength, flexural strength, unit weight, ultrasonic transmission rate and capillarity coefficient determination tests were applied to the produced geopolymer mortar samples and the results of the experiments were analyzed by Taguchi method. The highest compressive strength value of 24.27 MPa was obtained with Elazig ferrochrome slag without cement and the optimum levels of the parameters were determined by analysis of variance [31].

In the study where the Taguchi-Grey relational analysis method was used for the systematic evaluation and efficient recycling of blast furnace slag and paper production waste (PPW) for reuse, the setting time, compressive strength, flexural strength, and tensile strength of the produced mortar were analyzed. Four types of PPW-blast furnace slag specimens were prepared: lime mud, primary sludge, fly ash and bottom ash. It was found that PS content affected the setting time, bottom ash content affected the flexural and compressive strengths, and bottom ash and lime mud content affected the degree of shrinkage and the most suitable PPW-BFS mortar composition was lime mud: 5%; primary sludge: 5%; fly ash: 30%; bottom ash: 10% [32].

The Taguchi method is efficiently used for fractional factorial design of materials. This method is based on the principles of using orthogonal arrays [33, 34]. The optimum combination is determined based on the signal-to-noise ratio (S/N) and is used to understand the effects of each parameter on the responses.
Several studies have been conducted using the Taguchi method to convert complex waste compositions into construction materials [32, 35, 36]. The Taguchi method is efficiently utilized for examining waste materials with complex compositions, but its disadvantage is that it can only be used to optimize a single objective. Therefore, this limitation restricts the application possibilities of the method. Upon reviewing the literature, it can be observed that there is a limited number of studies focusing on the use of brick waste through alkali activation method.

In this study, mortar production was carried out using the alkali activation method with different concentrations of NaOH (6 M, 8 M, and 10 M) and AA/PM ratios (0.30, 0.35, 0.40) of hollow brick powder waste. The compressive and flexural strength tests were applied to the samples. The optimum mixture ratios were determined using the Taguchi L9 (3^2) orthogonal array design based on the obtained experimental results. There is a need for new approaches for the reuse of waste materials generated after construction and demolition applications [37].

Recycling of demolition wastes is one of the important subjects with high added value and has been studied in recent years. In addition, the utilization of building demolition wastes in this way is environmentally effective. Therefore, it is believed that this research will contribute to the existing literature with the use of Taguchi method in determining the mixing ratios of BFS and HBW based AAC systems.

1. Material and Method

1.1. Materials and mixture ratios

In the preparation stage of alkali-activated mortar samples, finely ground blast furnace slag (BFS) obtained from Oyak Bolu Çimento Ereğli Facility was used. The chemical and physical properties of the BFS and HBW used in the study are shown in Table 1. AFS 30-35 silica sand was used in the mixtures. HBW obtained from the Duzce region were ground and used after passing through a 4 mm sieve in the laboratory. In addition, the sieve analysis of the BFS and HBW are shown in Figure 1. Sika ViscoCrete SF-18 high-performance superplasticizer (brown; density: 1.25 g/cm^3) obtained from Sika Construction Chemicals was used to increase the workability of composite mixtures. In addition, liquid Sodium Hydroxide (NaOH) (colorless; density: 1.507 g/cm^3) and liquid Sodium Silicate

Table 1. Chemical properties of BFS and hollow brick powder waste

	SiO_2	Fe_2O_3	TiO2	Al_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Mn_2O_3	Cr_2O_3
BFS	38.86	0.71	2.03	13.23	37.71	4.15	0.47	0.54	0.01	0.74	0.01
HBW	59.78	9.04	1.02	21.24	1.92	1.73	0.67	2.97	0.00	0.19	0.03

(Na_2SiO_3) (colorless; density: 1.431 g/cm^3) were used as alkali activators.

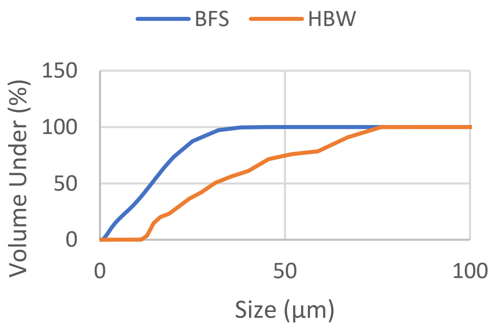

Figure 1. Sieve analysis of the BFS and HBW

Na_2SiO_3 was added to the mixture at a ratio of 2 for the prepared mortar. The mixture ratios of the produced alkali-activated composites are given in Table 2.

1.2. Preparation of mortar samples

For the compressive strength tests, molds with dimensions of 50x50x50 mm were used, and for the flexural strength tests, molds with dimensions of 40x40x160 mm were used (Fig. 2). NaOH solutions prepared as 6M, 8M and 10M were mixed until homogeneous. The materials to be used for the mortar specimens were weighed separately in individual containers and prepared. For the prepared mortar, sodium silicate (Na_2SiO_3) was added to achieve a Na_2SiO_3/NaOH ratio of 2 [38, 39].

Figure 2. Beam and cubic molds used in experiments

While the powder materials were mixed in the mixer at low speed (62.5 rpm) for 60 seconds, a homogeneous mixture of alkali activator and super plasticizer was ensured during this time. After 60 seconds, the alkaline activators were added to the powdered samples, and the mixtures were mixed at a high speed (125 rpm) for 150 seconds. After mixing, the homogeneity of themortar was checked, and if necessary, it was mixed again for 60 seconds (Fig. 3). The mortar was placed in lubricated molds and compacted thoroughly on the shaking table. After the mortars placed in the molds were covered with stretch film, they were kept in an oven at 90°C for 24 hours and when the samples reached room temperature, compressive and flexural strength tests were conducted.

1.3. Compressive strength tests

Compressive strength tests were carried out according to the ASTM C109 (2020) standard. Compressive strength tests were performed on the prepared cube specimens with an application rate of 0.5 MPa/s (Fig. 4a). The averages of the obtained results were calculated, and the compression strength values were determined using Equation 1.

Table 2. Mixing ratios of alkali-activated composite samples

Mix Type	BFS (%)	HBW (%)	Silica sand (%)	SP* (%)	NaOH (%)	Na_2SiO_3 (%)	AA/PM
6 M NaOH	21.90	32.80	21.90	0.40	7.60	15.20	0.30
	24.57	24.57	24.57	0.50	8.60	17.20	0.35
	23.70	23.70	23.70	0.50	9.50	19.00	0.40
8 M NaOH	21.90	32.80	21.90	0.40	7.60	15.20	0.30
	24.57	24.57	24.57	0.50	8.60	17.20	0.35
	23.70	23.70	23.70	0.50	9.50	19.00	0.40
10 M NaOH	21.90	32.80	21.90	0.40	7.60	15.20	0.30
	24.57	24.57	24.57	0.50	8.60	17.20	0.35
	23.70	23.70	23.70	0.50	9.50	19.00	0.40

*** Super Plasticizer**

$$R_c = \frac{F_c}{Area} \quad (1)$$

In the formula, R_c represents the compressive strength (MPa), F_c represents the maximum load reached at the point of failure (N), and Area represents the cross-sectional area of the specimen (expressed in mm²).

Figure 3. Mixing materials and mixer

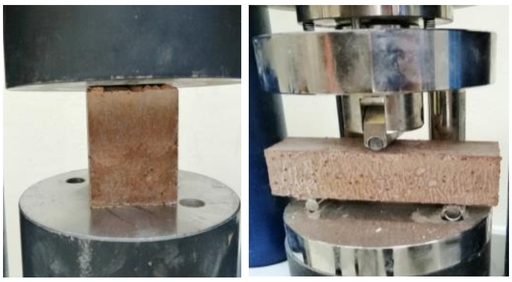

Figure 4. a) Compressive and **b)** Flexural strength test specimens

1.4. Flexural strength tests

Flexural strength tests were conducted according to the TS EN 1015–11/A1 (2013) standard. The three-point bending test method based on the simple beam principle was used in the study. Flexural strength tests were conducted at a loading rate of 0.05 MPa/s (Fig. 4b). The flexural strength calculation was made according to the results obtained by using the formula in Equation 2. In the formula, σ: the flexural strength (N/mm²), P: the force acting at the moment of fracture (N), L: the distance between the two supports (mm), b: the beam width (mm), and d: the beam height (mm).

$$\sigma = \frac{3PL}{2bd^2} \quad (2)$$

1.5. Taguchi method

The Taguchi method is a statistical approach based on the principle of determining the most suitable parameter to achieve a high-quality product or process design. In this method, the most significant factors that affect product quality are identified during the product development stage, and the optimum parameters are determined by statistical analysis of these factors in order to obtain the desired result [33]. The Taguchi method allows for the reduction of the number of experiments required to obtain the desired quality product by identifying the most important parameters. This contributes positively in terms of both time and cost [34].

In the Taguchi method, the Signal-to-Noise (S/N) ratio is a measure that determines the performance of a product or process and ensures that the targeted output quality is achieved at the desired level. The S/N ratio is selected as the smallest-the better, the largest-the better, or the target value-the better, depending on the desired objective, in order to reach the desired goal. When calculating the S/N ratios, the smallest-the better is preferred when the output values need to be minimized, the largest-the better when they need to be maximized, and the target value-the better when they need to match a specific nominal value [40]. In this study, optimization was performed using the Taguchi method with the predetermined parameters and levels, and the best mixing ratios were determined. The L9 (3^2) Taguchi orthogonal index was chosen with 3 concentrations of NaOH of 6M, 8M and 10M and AA/PM 0.30, 0.35 and 0.40 ratios with 3 levels (Table 3).

Table 3. Experimental parameters and levels

Parameter	Level	Value
NaOH	3	6M, 8M , 10M
AA/PM	3	0.30, 0.35, 0.40

2. Result and Discussion

When examining Table 4, it can be observed that an increase in NaOH molarity and AA/PM ratio leads to a decrease in compressive strength values [41]. The amount of Na_2O present in the NaOH solution plays an important role in the development of compressive strength. 6 M and higher NaOH concentration increases the amount of Na^+ cation and causes higher alkalinity [42]. However, specimens with high alkali content show a decrease in compressive strength due to the rapid precipitation of aluminosilicates at early ages and the formation of a porous microstructure. In addition, higher NaOH concentration leads to a weakening of the gel structure due to excess hydroxide ions and a decrease in the availability of Si, Al and Ca [43]. During the analysis of compressive strength values using the Taguchi method, Equation 3 was preferred by considering the larger-the-better case since it is desired to have high compressive strength values for the specimens in the calculation stage of the S/N ratios.

2.1. Compressive strength results

The test results of compressive strength for the prepared AACs are shown in Table 4.

Table 4. Compressive strength results

NaOH	AA/PM	Compressive Strength Results (MPa)*	*SD
6 M	0.30	63.669	±4.930
	0.35	45.906	±6.004
	0.40	34.284	±5.221
8 M	0.30	38.216	±2.962
	0.35	37.405	±2.691
	0.40	37.996	±2.795
10 M	0.30	30.603	±2.248
	0.35	29.219	±1.648
	0.40	26.461	±2.127

***Standard Deviation**

$$S/N = -10\log(\frac{1}{n}\sum_{i=1}^{n} = 1\,\frac{1}{yi^2}) \quad (3)$$

The highest S/N graph and S/N ratios in the response table obtained using the Taguchi method to achieve the optimum parameter (NaOH and AA/PM) values for Figure 4 and Table 5 are shown. According to Figure 4, the highest S/N ratio was obtained at a parameter level of 6 M NaOH and an AA/PM ratio of 0.30.

Table 5. S/N ratios obtained according to compressive strength values

NaOH	AA/PM	S/N
6 M	0.30	36.078
	0.35	33.237
	0.40	30.701
8 M	0.30	31.645
	0.35	31.458
	0.40	31.594
10 M	0.30	29.715
	0.35	29.313
	0.40	28.452

Furthermore, Variance (ANOVA) analysis was conducted to determine the effect of the pressure resistance experimental parameters (Table 6).

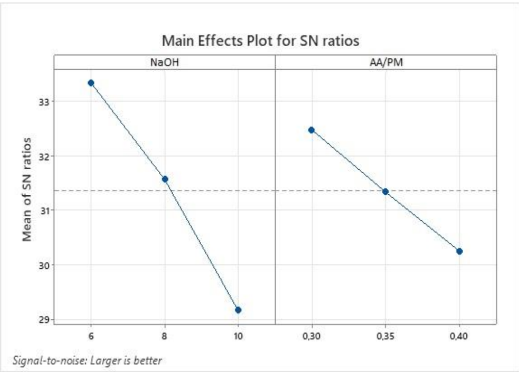

Figure 4. S/N ratios compressive strength according to parameter levels

When Table 6 is examined, the fact that the P value for NaOH is lower than that of AA/PM shows that it is a more influential parameter. The parameter with the higher F value is again the NaOH parameter. When analyzing the impact ratios of the parameters on the compressive strength results, it can be observed that the most influential parameter is NaOH with a percentage of 55.28%.

2.2. Flexural strength results

The average values of the flexural strength results obtained from 9 series activated with alkali prepared using different ratios of NaOH and AA/PM are given in Table 7. It is seen that the flexural strength values decrease with the increase in the NaOH ratio in Table 7. The flexural strength follows a similar trend to the compressive strength, with a significant decrease observed when the NaOH concentration rises from 6 M to 10 M. This decrease in the flexural strength values may be attributed to the change in the microstructure of HBW-based samples due to the increase in NaOH concentration. While the analysis of flexural strength values using the Taguchi method, Equation 3 was preferred, considering the larger-the-better case, as higher flexural strength values for the mortars were desired during the calculation stage of the S/N ratios.

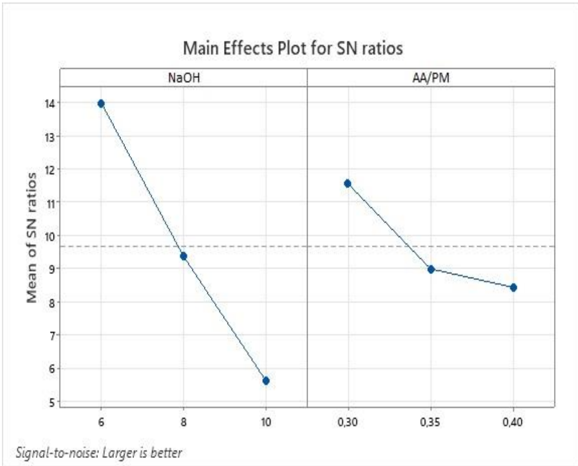

Figure 5. S/N ratios flexural strength by parameter levels

The graph of the flexural strength values analyzed using the Taguchi method according to parameter levels is given in Figure 5, and the S/N ratios are provided in Table 8. When examining Table 8, the lower P-value for NaOH compared to AA/PM indicates that NaOH is a more influential parameter. The parameter with a high F-value is also NaOH. When analyzing the impact ratios of the parameters on the flexural strength results, it can be observed that the most influential parameter is NaOH with a percentage of 75.47%.

Table 6. Analysis of variance results for compressive strength values

Parameter	Degree of Freedom	Effect Ratio	Sum of Squares	Mean of Squares	F-Value	P-Value
NaOH	2	55.28%	553.0	276.48	4.33	0.100
AA/PM	2	19.19%	192.0	95.98	1.50	0.302
Error	4	25.53%	255.3	63.84		
Total	8	100.00%				

Table 7. Flexural strength results

NaOH	AA/PM	Flexural Strength Results (MPa)*	*SD
6 M	0.30	6.629	±0.588
	0.35	5.079	±0.939
	0.40	3.721	±0.910
8 M	0.30	3.602	±0.315
	0.35	2.894	±0.341
	0.40	2.437	±0.472
10 M	0.30	2.266	±0.573
	0.35	1.518	±0.235
	0.40	2.030	±0.259

***Standard Deviation**

Table 8. S/N ratios according to flexural strength values

NaOH	AA/PM	S/N
6 M	0.30	16.428
	0.35	14.115
	0.40	11.413
8 M	0.30	11.129
	0.35	9.229
	0.40	7.736
10 M	0.30	7.103
	0.35	3.625
	0.40	6.148

The highest S/N ratio was obtained at the parameter levels of 6 M NaOH and an AA/PM ratio of 0.30. Additionally, Variance analysis was conducted to determine the effect of the flexural strength experimental parameters (Table 9).

3. Conclusion

In this study, the compressive and flexural strength of alkali-activated mortars produced using high furnace slag and hollow brick waste were investigated. The parameters determined using the Taguchi method were optimized for the best mixture ratios using the L9 (3^2) orthogonal array. The following data were obtained as a result of the study:

- The lowest compressive strength was obtained from 10M NaOH with 26.461 MPa, and the highest compressive strength was obtained from 6M NaOH with 63.669 MPa. It was observed that as AA/TM increased from 0.30 to 0.40, the compressive strength of 6M NaOH, 8M NaOH and 10M NaOH decreased by 46%, 0.5% and 14%, respectively.

- The highest flexural strength was obtained from 6M NaOH with 6.629 MPa, and the lowest flexural strength was obtained from 10M NaOH, 1.518 MPa. It was observed that as AA/TM increased from 0.30 to 0.40, the flexural strength of 6M NaOH, 8M NaOH and 10M NaOH compressive strength decreased by 44%, 32% and 11%, respectively.

- When evaluating the compressive and flexural strength results according to the AA/PM ratios used (0.30, 0.35, and 0.40), it was observed that the highest value was obtained at a ratio of 0.30.

- According to the experimental results of compressive and flexural strength, it was observed that the highest strength values were obtained at 6 M, while the lowest values were obtained at 10 M.

Table 9. Analysis of variance results for flexural strength values

Parameter	Degree of Freedom	Effect Ratio	Sum of Squares	Mean of Squares	F-Value	P-Value
NaOH	2	75.47%	16.044	8.0222	16.37	0.012
AA/PM	2	15.31%	3.255	1.6276	3.32	0.141
Error	4	9.22%	1.960	0.4090		
Total	8	100.00%				

- Optimum values were determined by conducting a variance analysis using the Taguchi method based on the obtained compressive and flexural strength results. According to this analysis, it was observed that the best values were obtained at 6 M NaOH and an AA/PM ratio of 0.30.

- Additional research can be conducted with alkaline activated mortar mixtures by changing the parameters and levels determined in this study. It is also possible to improve the study by using different waste materials, changing activator types or additives.

Article Information Form

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Authors' Contribution

The author confirms sole responsibility for the following: Study conception and design, data collection, analysis and interpretation of results, and manuscript preparation

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author of the paper declares that he complies with the scientific, ethical, and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, he declares that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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