Journal of Mines, Metals and Fuels, *73(3): 611-618; 2025. DOI: 10.18311/jmmf/2025/47440*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Exploring the Utilization of Zeolite as a Supplementary Component in Concrete Along with Predictive Strength Modeling via Regression Analysis Techniques

Sushant Waghmare[1]*and Gopi Ghadvir[2]

[1]Department of Civil Engineering, DY Patil College of Engineering, Pune - 411044, Maharashtra, India; sushantvwaghmare@gmail.com

[2]Department of Civil Engineering, Pimpri Chinchwad University, Pune - 412106, Maharashtra, India

Abstract

This research paper explores the exciting potential of adding zeolite to concrete mixes, aiming to see how practical and effective this approach can be. Zeolite is a naturally available mineral known for its exclusive qualities, making it an intriguing alternative to traditional concrete additives. With its high surface area, porous structure, and ability to act as molecular sieves, zeolite can significantly impact the physical and chemical properties of concrete. Using regression analysis, we aim to predict the strength of concrete mixtures with varying amounts of zeolite. This statistical method helps us to understand how different proportions of zeolite affect concrete strength. By developing predictive models, we seek to quantify the impact of zeolite on concretes performance. Our experiments involve preparing multiple concrete batches with different zeolite content and rigorously testing them for key properties like compressive strength, workability, and durability. The data from these experiments give us a detailed understanding of how zeolite influences concrete. The discoveries from this research deliver treasured perceptions into the practical use of zeolite in concrete manufacturing, potentially enhancing performance, sustainability, and cost-efficiency. We hope to show that zeolite can improve concretes mechanical properties while reducing the need for traditional, often more expensive, additives. Moreover, using zeolite, a more environmentally friendly material, can help the construction industry meet its sustainability goals by lowering the carbon footprint of concrete production. Ultimately, we aim to encourage the broader adoption of zeolite in concrete applications, promoting innovations that benefit both the economy and the environment.

Major Findings: *This study demonstrates that incorporating zeolite into concrete enhances its mechanical properties, workability, and durability while reducing the reliance on conventional additives. Predictive models using regression analysis reveal the optimal zeolite content for improved concrete performance. The findings emphasize zeolite's potential to promote sustainability and cost-efficiency in concrete manufacturing.*

Keywords: *Concrete, Predictive Strength Modeling, Regression Analysis, Supplementary Material, Zeolite*

1.0 Introduction

Zeolite, a natural pozzolan, shows promise as a supplementary material in concrete to enhance its mechanical properties and sustainability[1-5]. Studies reveal that zeolite can improve the compressive strength of concrete by acting as a pozzolanic material. Incorporating zeolite in cement formulations can lead to increased strength, reduced permeability, and enhanced petro-physical properties. Additionally, zeolite can delay hydration, requiring longer curing times for optimal strength development, while also effectively absorbing

**Author for correspondence*

heavy metals, making it environmentally beneficial. The usage of zeolite as a fractional replacement for cement can reduce the carbon footprint of concrete production, offering a sustainable solution to minimize CO_2 emissions. Overall, zeolite presents a viable option for improving the performance and environmental impact of concrete structures.

Many of the research efforts are primarily directed towards exploring new applications of zeolites in concrete. Zeolites, known for their pozzolanic behavior and ability to absorb heavy metals, are being investigated for their potential to enhance the properties of concrete[6]. Additionally, advancements in synthetic methodologies have led to the development of new zeolite materials with high performance in catalytic production and separations, offering promising applications in diverse fields[7]. Characterization techniques like atom probe tomography and scanning transmission X-ray microscopy are being employed to better understand zeolite-based materials, aiding in the exploration of their properties and applications in sustainable practices. Furthermore, the synthesis, characterization, and catalytic applications of multifunctional heteroatom zeolites are being actively researched to boost further studies in this area[8].

The inclusion of zeolites in concrete has shown various beneficial effects on its physical and mechanical properties. Many research has demonstrated that Zeolite Powder (ZP) can augment the volume stability of concrete by reducing dry shrinkage and creep, while also improving the microstructures compactness[9]. Additionally, zeolites added to Class-H cement have been found to increase compressive strength, reduce permeability, and enhance petro physical properties, with the 5% zeolite formulation showing optimal results. Furthermore, synthetic zeolite polymer composites have been shown to improve the hydration reaction of ordinary Portland cement, leading to increased compressive and flexural strength of cement mortar, especially at early stages[10]. Incorporating zeolites in concrete mixtures, alongside other additives like profillite, has been found to significantly enhance compressive and flexural strengths, thermal conductivity, and dry bulk density, suggesting their potential for durable lightweight concrete designs.

The main objective of this research is to develop and test the several regression models using ANN, SPSS, Excel and Python. Several regression tools available in Python are used for development and analysis of model which can foresee the compressive strength of Zeolite blended concrete. This paper also focuses on applicability of Zeolite in concrete manufacturing to reduce overall carbon emission due to manufacture of cement.

2.0 Literature Review

Current research on zeolite in concrete applications focuses on enhancing properties and sustainability. Studies explore zeolites role as a pozzolanic material, improving durability and reducing carbon footprint by partially replacing cement[11,12]. Zeolite's ability to delay hydration, leading to denser structures over time, is noted, along with its effectiveness in absorbing heavy metals, contributing to lower leached heavy metals in cement paste[13]. Additionally, zeolite is investigated as a mineral admixture to enhance physical and mechanical properties of cement mortars, particularly improving drying shrinkage reduction and frost resistance[18]. The potential of zeolites in gas separation, purification, and heterogeneous catalysis is also highlighted, showcasing their versatility in various industrial applications[14].

The literature reviewed on properties and characteristics of zeolite relevant to concrete production focuses on enhancing concrete performance while addressing environmental concerns. Studies show that incorporating natural zeolite in concrete can improve durability, mechanical properties, and reduce environmental impact[15]. Zeolites, especially superfine zeolites, can replace part of the cement, reducing consumption and the carbon footprint of concrete production[16]. Additionally, zeolites exhibit high sorption capacity, making them effective in pollutant removal and as reservoirs of water and nutrients for plants, benefiting agriculture and sustainable development[17]. Furthermore, zeolite-blended concrete with up to 30% cement replacement shows delayed hydration but gains strength over time, with the added benefit of absorbing heavy metals, contributing to improved durability and environmental safety[18].

Present research on existing methodologies for predictive strength modeling in concrete includes the utilization of various advanced algorithms and techniques. Machine learning algorithms like the Gradient Boosting Regression Tree (GBRT) have shown excellent accuracy in

predicting concrete compressive strength[19]. Additionally, the integration of Artificial Electric Field Algorithm with Neuro-Fuzzy Networks (AEFA+NFN) has been proposed for accurate strength prediction, outperforming other methods. Furthermore, the use of an optimized BP neural network model, enhanced by Spearman and PCA methods, has significantly improved prediction accuracy by reducing errors and optimizing input variables. These methodologies showcase the advancements in predictive modeling for concrete strength, offering more accurate and efficient ways to forecast compressive strength in construction projects.

3.0 Methodology

The initial phase of testing in this research purposes to assess the influence of Zeolite on the strength characteristics of cement. To accomplish this goal, various percentages of Zeolite (0%, 5%, 10%, 15%, and 20%) are substituted for cement. Subsequently, cement cubes are fabricated and subjected to compression tests to ascertain their compressive strength.

Table 1 below presents the compressive strength values of cement for different levels of zeolite substitution.

From Figure 1, it has been observed that Mortar, when cement is replaced with 10% Zeolite, yields the most favorable compressive strength values. Consequently, in the following stages, the replacement level of zeolite is settled at 10%.

Selecting zeolite samples and concrete mix proportions are two important processes in the development of concrete structures that are more durable and sustainable. Zeolites have special properties of porous structure and exchange of ions make them ideal to use as supplementary cementitious materials in the production of concrete. The choice of zeolite samples is dependent on several factors, such as chemical composition, particle size distribution, and pozzolanic activity. Furthermore, the use of zeolites in concrete mixtures involves mix proportions affecting properties like compressive strength that must not be compromised. Furthermore, laborious testing is essential to authenticate their efficiency and suitability for specific applications, ultimately contributing to the advancement of sustainable construction practices.

Concrete mix proportion is done to satisfy the prequisite performance of concrete such as workability, strength and durability. It helps in deciding the proportion of ingredients of concrete.

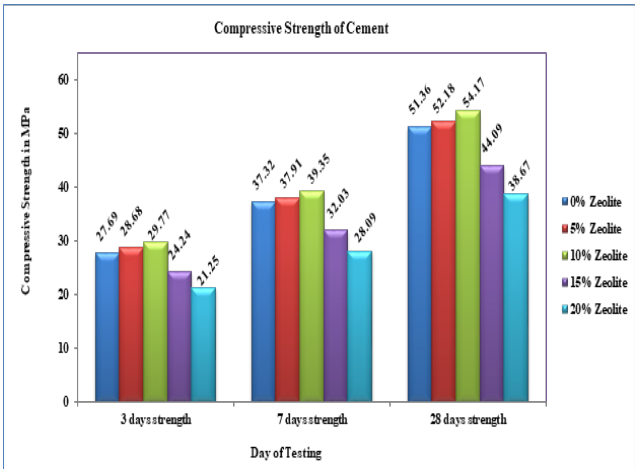


Figure 2. Compressive strength of cement for varying percent of zeolite.

Table 1. Compressive strength of cement for varying percent of zeolite

Day of Testing	0% Zeolite	5% Zeolite	10% Zeolite	15% Zeolite	20% Zeolite
3 Days strength	27.69	28.68	29.77	24.24	21.25
7 Days strength	37.32	37.91	39.35	32.03	28.09
28 Days strength	51.36	52.18	54.17	44.09	38.67

Table 2. Mix design and proportions

Ingredient in Kg/m^3				Mix Ratio
Cement	Fine Aggregate	Coarse Aggregate	Water	
361	713.90	1270.50	123.5	1 : 1.979: 3.521



Figure 2. Compressive strength test on concrete specimen.

IS: 10262-2009; IS: 456-2000, IS: 383-1970 and IRC: 44-2017 is referred for concrete mix design. The target mean strength of 48.25 MPa of mix is designed without additives.

Table 2 demonstrates the particulars of mix quantities.

The strength properties of zeolite combined concrete is investigated by casting specimens and tested for its strength in respective equipment and machinery. Following Figure 2 shows the testing of concrete cube specimen and testing using concrete testing machine.

The samples are tested after curing span of 28 days to calculate the compressive strength of cube sample. Total 45 cube samples are tested and results are recorded in tabular form. Above Figure 3 demonstrate the comparison of compressive strength of concrete samples with varying

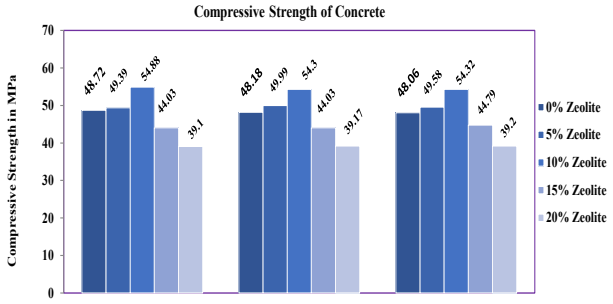


Figure 3. Comparison of compressive strength of concrete.

percentage of zeolite. The findings show that the ideal outcome is achieved with a 10% blend of Zeolite. It's noted that there is a steady upsurge in compressive strength up to the 10% mark, but beyond that, there is a decline in compressive strength.

4.0 Regression Analysis Techniques Employed for Strength Prediction Modeling

Researchers often use regression analysis to figure out how different things, like the ingredients in concrete or how it is made, affect how strong it turns out to be. There are different types of regression methods they use, each with its strengths. In this study, several regression models are used for strength prediction. Following Table 3 shows tools of regression are used in this study:

Table 3. Regression tools used

Software	Name of Tool	Abbreviation Used
MatLab	Neural Network tool	ANN
IBM SPSS	Regression tool	SP
MS-Excel	Data Analysis tool	ME
Python (Jupyter Notebook)	Linear Regression	LR
	Ridge Regression	RR
	Neural Network Regression	NNR
	Lasso Regression	LR
	Decision Tree Regression	DTR
	Random Forest	RF
	KNN Model	KNN
	Support Vector Machines	SVM
	Polynomial Regression	PR

The basic methodology behind using the model is to train the regression model using dataset prepared using previous literature. The totals of 603 mix design values are

Table 4. Comparison between actual and predicted values

Ex	ME	SP	ANN	LR	RR	NNR	LR	DTR	RF	KNN	SVM	PR
48.72	49.21	47.66	57.50	49.21	47.51	48.23	45.50	49.00	47.80	37.32	41.45	48.81
48.18	49.21	47.66	57.50	49.21	47.51	48.23	45.50	49.00	47.80	37.32	41.45	48.81
48.06	49.21	47.66	57.50	49.21	47.51	48.23	45.50	49.00	47.80	37.32	41.45	48.81
49.39	49.21	47.66	57.50	49.70	47.98	49.13	45.94	49.00	47.85	39.24	41.60	49.23
49.99	49.21	47.66	57.50	49.70	47.98	49.13	45.94	49.00	47.85	39.24	41.60	49.23
49.58	49.21	47.66	57.50	49.70	47.98	49.13	45.94	49.00	47.85	39.24	41.60	49.23
54.88	49.21	47.66	57.50	50.20	48.46	49.97	46.38	49.26	48.24	39.24	41.75	49.65
54.30	49.21	47.66	57.50	50.20	48.46	49.97	46.38	49.26	48.24	39.24	41.75	49.65
54.32	49.21	47.66	57.50	50.20	48.46	49.97	46.38	49.26	48.24	39.24	41.75	49.65
44.03	49.21	47.66	57.50	50.69	48.94	50.78	46.81	49.26	48.69	40.82	41.90	50.08
44.03	49.21	47.66	57.50	50.69	48.94	50.78	46.81	49.26	48.69	40.82	41.90	50.08
44.79	49.21	47.66	57.50	50.69	48.94	50.78	46.81	49.26	48.69	40.82	41.90	50.08
39.10	49.21	47.66	57.50	51.18	49.41	51.61	47.25	49.26	48.74	40.18	42.06	50.51
39.17	49.21	47.66	57.50	51.18	49.41	51.61	47.25	49.26	48.74	40.18	42.06	50.51
39.20	49.21	47.66	57.50	51.18	49.41	51.61	47.25	49.26	48.74	40.18	42.06	50.51

*Experimental Value

Table 5. Difference in results between actual and predicted values

ME	SP	ANN	LR	RR	NNR	LR	DTR	RF	KNN	SVM	PR
0.49	-1.06	8.78	0.49	-1.21	-0.49	-3.22	0.28	-0.92	-11.4	-7.27	0.09
1.03	-0.52	9.32	1.03	-0.67	0.05	-2.68	0.82	-0.38	-10.86	-6.73	0.63
1.15	-0.4	9.44	1.15	-0.55	0.17	-2.56	0.94	-0.26	-10.74	-6.61	0.75
-0.18	-1.73	8.11	0.31	-1.41	-0.26	-3.45	-0.39	-1.54	-10.15	-7.79	-0.16
-0.78	-2.33	7.51	-0.29	-2.01	-0.86	-4.05	-0.99	-2.14	-10.75	-8.39	-0.76
-0.37	-1.92	7.92	0.12	-1.6	-0.45	-3.64	-0.58	-1.73	-10.34	-7.98	-0.35
-5.67	-7.22	2.62	-4.68	-6.42	-4.91	-8.5	-5.62	-6.64	-15.64	-13.13	-5.23
-5.09	-6.64	3.2	-4.1	-5.84	-4.33	-7.92	-5.04	-6.06	-15.06	-12.55	-4.65
-5.11	-6.66	3.18	-4.12	-5.86	-4.35	-7.94	-5.06	-6.08	-15.08	-12.57	-4.67
5.18	3.63	13.47	6.66	4.91	6.75	2.78	5.23	4.66	-3.21	-2.13	6.05
5.18	3.63	13.47	6.66	4.91	6.75	2.78	5.23	4.66	-3.21	-2.13	6.05
4.42	2.87	12.71	5.9	4.15	5.99	2.02	4.47	3.9	-3.97	-2.89	5.29
10.11	8.56	18.4	12.08	10.31	12.51	8.15	10.16	9.64	1.08	2.96	11.41
10.04	8.49	18.33	12.01	10.24	12.44	8.08	10.09	9.57	1.01	2.89	11.34
10.01	8.46	18.3	11.98	10.21	12.41	8.05	10.06	9.54	0.98	2.86	11.31

used for training and testing of model. The distribution of entire data is divided into 70% and 30%, where 70% data is used for training and 30% data is used for testing the model.

The accuracy of regression model is judged based on the value of coefficient of determination (R^2 value) obtained after training and testing of the model. The range of R^2 obtained using regression models are more than 90% which shows the strong relation between input and output variables.

For the validation of the regression model, the test results obtained from laboratory test are used. In validation stage of modeling, comparative analysis is carried out between predicted value obtained from regression model and result obtained from laboratory tests.

Following Table 4 shows the comparison between actual and predicted compressive strength values.

As it can be seen from below Table 5, it has been observed that range of deviation amid actual and a predicted value of compressive strength is -7.82 to 10.317. Based on data obtained it can be seen that SPSS provides the most accurate prediction with average deviation of result is 0.477. In case of regression modelling carried out using Python, Lass Regression model has less deviation *i.e.* -0.807.

5.0 Discussion

This study aimed to sight see the utilization of zeolite as a supplementary component in concrete and evaluate its feasibility and efficiency through predictive strength modeling using regression analysis techniques. The results reveal that zeolite, a naturally occurring mineral with exclusive assets such as high surface area, porous structure, and molecular sieving capability; can considerably impact the physical and chemical characteristics of concrete.

The experimental results confirmed that integrating zeolite into concrete mixes enhanced the compressive strength, especially at certain optimal proportions. The pozzolanic reaction of zeolite contributed to a denser microstructure, which in turn improved the compressive strength of the concrete. Nevertheless, it is important to note that beyond a specific proportion; the strength gain remained same or even decreased, suggesting a threshold for the beneficial effects of zeolite.

The regression analysis provided a robust framework for envisaging the compressive strength of concrete mixtures incorporating different proportions of zeolite. The predictive models developed in this study showed high accuracy in estimating the strength outcomes based on the mix proportions. The use of regression analysis facilitated the understanding of the relationship between zeolite content and concrete strength.

6.0 Practical Implications

The practical consequences of integrating zeolite into concrete are manifold:

1. **Performance Enhancement**: Zeolite can be tactically used to boost the mechanical properties and durability of concrete, making it suitable for various construction applications where superior performance is required.
2. **Sustainability:** The use of zeolite aligns with sustainability goals by plummeting the dependence on traditional additives and lowering the carbon footprint of concrete production. Zeolite, being a natural and abundant mineral, offers an eco-friendly alternative to synthetic additives.
3. **Cost-Efficiency:** Although initial adjustments in mix design and material handling may incur additional costs, the long-term benefits of improved durability and performance can lead to cost savings in maintenance and repair.

7.0 Limitations and Future Research

1. Despite the promising results, this study has certain limitations:
2. **Scale of Experiments**: The experiments were conducted on a laboratory scale. Future research should aim at larger-scale field trials to validate the findings.
3. **Long-Term Performance**: The research primarily fixated on short-term properties. Long-term performance and durability trainings are essential to comprehensively recognize the benefits and potential drawbacks of using zeolite in concrete.
4. **Environmental Impact**: While zeolite is more environmentally friendly than traditional

additives, a detailed life cycle assessment is needed to fully quantify its environmental impact.

Future research should also explore the potential synergistic effects of combining zeolite with other supplementary cementitious materials. Additionally, advanced modeling practices, such as machine learning, could be employed to further enhance the predictive accuracy of concrete strength models.

8.0 Conclusion

This research has successfully demonstrated the potential of zeolite as a supplementary component in concrete. By enhancing compressive strength, workability, and durability, zeolite presents itself as a worthwhile alternative to traditional concrete additives. The incorporation of regression analysis techniques provided valuable predictive insights, simplifying the optimization of concrete mix designs. The discoveries from this work contribute to the growth of sustainable construction practices, encouraging innovations that align with both economic and environmental objectives. Further research and field applications will be crucial in realizing the full potential of zeolite in the concrete industry.

9.0 Declaration of 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.

10.0 References

1. Bohac M, Kubatova D, Necas R, Zezulova A, Masarova A, Novotny R. Properties of cement pastes with zeolite during early stage of hydration. Procedia Eng. 2016; 151:2-9. https://doi.org/10.1016/j.proeng.2016.07.349
2. Rudzionis Z, Adhikary SK, Manhanga FC, Ashish DK, Ivanauskas R, Stelmokaitis G, *et al*. Natural zeolite powder in cementitious composites and its application as heavy metal absorbents. J Build Eng. 2021; 43:103085. https://doi.org/10.1016/j.jobe.2021.103085
3. Prashant UL, Kumar HK, Syed AB. Study on utilization of zeolite and stone dust in concrete. IJETMS. 2020; 4(5):93-97. https://doi.org/10.46647/ijetms.2020.v04i05.017
4. Vissa SVK, Massion C, Lu Y, Bunger A, Radonjic M. Zeolite-enhanced Portland cement: Solution for durable wellbore-sealing materials. Matls. 2023; 16(1). https://doi.org/10.3390/ma16010030
5. He ZH, Han XD, Zhang ZD, Shi JY, Han C, Yuan Q, *et al*. Volume stability and nano-scale characteristics of concrete composite containing natural zeolite. J Build Eng. 2022; 59:105127. https://doi.org/10.1016/j.jobe.2022.105127
6. Li Y, Yu J. Emerging applications of zeolites in catalysis, separation and host-guest assembly. Nat Rev Mater. 2021; 6(12):1156-1174. https://doi.org/10.1038/s41578-021-00347-3
7. Vreeswijk SHV, Weckhuysen BM. Emerging analytical methods to characterize zeolite-based materials. Natl Sci Rev. 2022; 9(9). https://doi.org/10.1093/nsr/nwac047
8. Chunti K, Chakartnarodom P, Sonprasarn P, Prakaypan W, Laitila EA, Polsilapa S. Mechanical properties enhancement of the cement mortar by synthetic zeolite polymer composites. Suan Sunandha Sci Tech J. 2023; 10(1):120-125. https://doi.org/10.53848/ssstj.v10i1.429
9. Ramezanianpour AA, Amirani MMZ, Mirvalad S. Zeolite containing mortars reinforced with graphene oxide synthesized by hydrolysis of tetraethyl orthosilicate. J Mater Civ Eng. 2022; 34(6). https://doi.org/10.1061/(asce)mt.1943-5533.0004217
10. Cao G, Shah MJ, Dorset DL, Strohmaier KG, Brody JF. Synthesis and sorptive properties of EMM-8: A new (silico) aluminophosphate. In: Stud Surf Sci Catal. 2007; 170:311-313. https://doi.org/10.1016/s0167-2991(07)80854-8
11. Garrone E, Delgado MR, Bonelli B, Arean CO. Probing gas adsorption in zeolites by variable-temperature IR spectroscopy: An overview of current research. Mol. 2017; 22(9). https://doi.org/10.3390/molecules22091557
12. Milovic T, Supic S, Malesev M, Radonjanin V. The effects of natural zeolite as fly ash alternative on frost resistance and shrinkage of blended cement mortars. Sustde. 2022; 14(5). https://doi.org/10.3390/su14052736
13. Vejmelkova E, Konakova D, Kulovana T, Keppert M, Zumar J, Rovnanikova P, *et al*. Engineering properties of concrete containing natural zeolite as supplementary cementitious material: Strength, toughness, durability, and hygrothermal performance. Cem Concr Compos. 2015; 55:259-267. https://doi.org/10.1016/j.cemconcomp.2014.09.013
14. Chen JJ, Li LG, Ng PL, Kwan AKH. Effects of superfine zeolite on strength, flowability and cohesiveness of cementitious paste. Cem Concr Compos. 2017; 83:101-110. https://doi.org/10.1016/j.cemconcomp.2017.06.010

15. Jarosz R, Szerement J, Gondek K, Mierzwa-Hersztek M. The use of zeolites as an addition to fertilisers- A review. CATENA. 2022; 213:106125. https://doi.org/10.1016/j.catena.2022.106125
16. Li D, Tang Z, Kang Q, Zhang X, Li Y. Machine learning-based method for predicting compressive strength of concrete. Proc. 2023; 11(2). https://doi.org/10.3390/pr11020390
17. Jibril MM, Malami SI, Muhammad UJ, Bashir A, Usman AG, Salami BA, *et al*. High strength concrete compressive strength prediction using an evolutionary computational intelligence algorithm. Asian J Civ Eng. 2023; 24(8):3727-3741. https://doi.org/10.21203/rs.3.rs-2933621/v1
18. Wang K, Ren J, Yan J, Wu X, Dang F. Research on a concrete compressive strength prediction method based on the random forest and LCSSA-improved BP neural network. J Build Eng. 2023; 76:107150. https://doi.org/10.1016/j.jobe.2023.107150
19. Zhang X, Wang B, Chang J. Variation in mineral composition by hydration and carbonation in calcium hydroxide matrix containing zeolite. J Build Eng. 2022; 56:104491. https://doi.org/10.1016/j.jobe.2022.104491