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Predictive Modeling of Concrete Water Penetration Depth Based on Material Properties

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Abstract: This research presents an enhanced model for estimating water penetration depth in concrete, developed through linear regression analysis using SPSS statistical software. The model incorporates critical concrete properties, including compressive strength, tensile strength, sorptivity, alkalinity, binder content, and water-cement ratio. Concrete mixes were prepared with three types of cementitious materials: Silica Fume, Slag, and Fly Ash. The results demonstrated that Silica Fume mixes achieved the lowest water penetration depth, indicating the highest resistance to permeability. Slag mixes followed, with Fly Ash mixes showing the greatest permeability. The model's predictions align closely with findings from previous studies, underscoring its accuracy and practical value, where the absolute value of the Mean Percentage Error (MPE) was found to be 1.64%, which indicates the accuracy of the proposed model in predicting the values. This demonstrates the model's effectiveness in making reliable predictions. This study highlights the significance of utilizing advanced statistical models to enhance concrete quality, guide material selection, and improve the durability and performance of structures across diverse environmental conditions.

Keywords: water penetration depth, permeability, sorptivity, alkalinity, spss.

1. INTRODUCTION

Permeability is a critical property of concrete that influences both its performance and durability. It denotes the ability of water or other liquids to penetrate through the concrete matrix, which is essential for evaluating how well concrete withstands environmental and mechanical stresses over time. Accurately measuring concrete permeability involves complex and time-consuming processes, including sample preparation, drying, and applying hydraulic pressure for extended periods [1]. This complexity underscores the need for a predictive model that estimates water penetration depth based on various factors, thereby optimizing testing procedures and reducing associated costs. Research indicates that several properties of concrete affect its water penetration depth, which serves as a key indicator of permeability. Compressive strength is a major factor, impacting the concrete's resistance to cracking and its effectiveness in preventing water ingress [2] [3] [4]. Additionally, fiber-reinforced concrete shows a significant improvement in compressive strength and splitting tensile strength, reflecting the impact of fibers in enhancing the mechanical integrity of the concrete structure. This is associated with the reduction of concrete porosity, thereby reducing its permeability [5]. Similarly, tensile strength plays a crucial role in minimizing cracks and limiting pathways through which water might permeate [6] [7]. It can be said that there is a complex relationship between permeability and compressive and tensile strength in concrete, where this relationship is influenced by the type and proportions of the added materials as well as the curing system used [8]. The sorptivity of concrete, which measures its ability to absorb water through capillary action, directly influences the availability of moisture for penetration [9], where some studies have shown a close correlation between permeability and sorptivity [10]. Alkalinity also matters, as a higher pH can form a protective passive layer on the concrete surface [11] [12]. The composition of binder materials, including the type and quantity of cement and supplementary cementitious materials, affects the concrete's microstructure and permeability [13]. Additionally, the water-to-cement ratio is a significant factor; lower ratios typically result in denser concrete with reduced porosity, enhancing resistance to water infiltration [14] [15] [16]. Understanding the factors affecting concrete permeability is crucial for assessing its long-term performance and durability. This research presents a predictive model for water penetration depth in concrete based on several influential properties. The model integrates key factors such as compressive strength, tensile strength, sorptivity, alkalinity, water-to-cement ratio, and the composition of binder materials. By using this model, the accuracy of predicting water penetration depth in concrete is enhanced, providing a more comprehensive assessment of the long-term performance and durability of concrete.

2. RESEARCH SIGNIFICANCE.

While existing literature provides comprehensive insights into how properties such as compressive strength, tensile strength, absorption, alkalinity, binder content, and water-to-cement ratio influence permeability, there remains a notable gap in effectively applying predictive models to integrate these variables. Previous studies have often focused on individual factors or limited combinations, but have not fully utilized advanced predictive techniques. This research addresses this gap by developing a new predictive model for water penetration depth in concrete, reflecting its permeability through the analysis of laboratory data. Using linear regression analysis with SPSS software, this study aims to provide a holistic understanding of how multiple factors interact and contribute to water penetration. The approach used in the presented model is straightforward and simple, avoiding unnecessary complexity while still offering practical applicability. The model's outcomes are expected to streamline testing processes, reduce costs, and offer valuable insights for engineers and practitioners to improve concrete mix designs and enhance structural durability under various environmental conditions.

3. MATERIALS USED IN THE STUDY

In this study, a single type of Ordinary Portland Cement (OPC) Grade 52.5 was used. The concrete mixtures incorporated natural silica sand with known physical properties and medium grading, and the aggregates were sourced from dolomite with a nominal maximum size of 10 millimeters. Additionally, some mixtures were enhanced with a high-range water-reducing admixture, specifically a water-based solution of modified polycarboxylate ether, branded as PVF. The PVF admixture was used to improve the workability and strength of the concrete while reducing water content. To further enhance the concrete's properties, the research also utilized Addicrete BVF 1, a high-performance admixture designed to enhance workability and strength while reducing water content. This admixture complies with ASTM C 494 Type F, ES 1899, and EN 934-2 standards. A dosage of 3.5 % of the cement weight was used. Addicrete BVF 1, with a density of 1.18 ± 0.01 kg/L at 25°C, can be added during the mixing process or pre-mixed with water. Table 1 presents the chemical composition of the cementitious materials used.

Table 1. The chemical composition of the cementitious materials used.

Component	Silica Fume	Slag	Fly Ash
SiO_2	97.79%	22%	50%
CaO	-	63%	5%
Al_2O_3	-	6%	25%
Fe_2O_3	-	4%	10%
MgO	-	3%	2%
$CaSO_4$	-	2%	-
Other Oxides	2.21%	-	8%

4. MIX PROPORTIONS

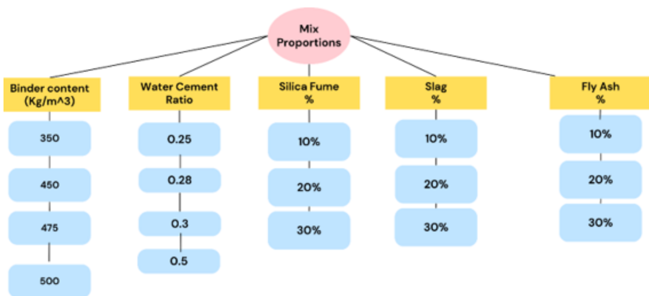

FIG 1. Mix proportions used in the study

Based on binder contents of 350, 450, 475, and 500 kg/m³ and water-to-cement ratios of 0.25, 0.3, 0.28, and 0.5, fourteen series of Ordinary Portland Cement (OPC) mixtures were created. These mixtures are categorized as follows: three mixtures with fly ash, at replacement ratios of 10%, 20%, and 30% of the cementitious content; three mixtures with silica fume, at similar replacement ratios; and three mixtures with slag, also at the same replacement ratios. Additionally, two high-strength mixtures were developed using silica, and one high-strength mixture was prepared without silica. Furthermore, two OPC mixtures were designed—one serving as a control and the other with low compressive strength—both without any additives. The mix proportions and components used in the study are detailed in Table 2, and Figure 1 illustrates the main mix ratios.

TABLE 2. Concrete mixtures utilized in the study

Mix no.	Cement Content (Kg/m3)	Water (Liter/m3)	Coarse Aggregate (kg/m3)	Sand (Kg/m3)	Silica % Replacement	Fly Ash % Replacement	Slag % Replacement	W/C	S.P %
Mix1	427.5	148.39	1190	595	10%	0	0	0.284	3.50%
Mix2	360	135.54	1190.7	595.353	20%	0	0	0.25	3.50%
Mix3	500	125	1254	627	0	0	0	0.25	3.50%
Mix4	450	135	1291	646	0	0	0	0.3	3.50%
Mix5	350	175	1277	638.5	0	0	0	0.5	0%
Mix6	405	135	1291	646	0	0	10%	0.3	3.50%
Mix7	360	135	1291	646	0	0	20%	0.3	3.50%
Mix8	315	135	1291	646	0	0	30%	0.3	3.50%
Mix9	405	135	1291	646	0	10%	0	0.3	3.50%
Mix10	360	135	1291	646	0	20%	0	0.3	3.50%
Mix11	315	135	1291	646	0	30%	0	0.3	3.50%
Mix12	405	135	1291	646	10%	0	0	0.3	3.50%
Mix13	360	135	1291	646	20%	0	0	0.3	3.50%
Mix14	315	135	1291	646	30%	0	0	0.3	3.50%

5. TESTS CONDUCTED IN THE STUDY

5.1 FRESH CONCRETE TESTS

The slump test was conducted on the fresh concrete for all mixtures according to ASTM C143 [14], and the slump results were recorded to assess workability and the properties of the fresh concrete, providing a better understanding of the impact of different admixtures and material proportions on the overall performance of the.

FIG 2. Slump Test Measurement

5.2 HARDENED CONCRETE TESTS

In this study, various tests were conducted to obtain the values of both dependent and independent variables. The permeability test measured the dependent variable, water penetration depth. Tests for some independent variables included compressive strength, tensile strength, alkalinity, and sorptivity. Figure 3 illustrates these tests and the corresponding specification numbers for each.

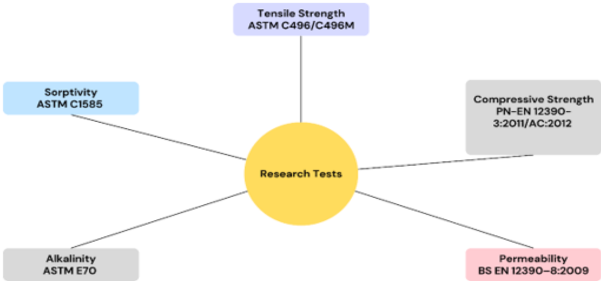

FIG 3. Tests conducted for hardened concrete

5.2.1 PERMEABILITY TEST

FIG 4. The water pressure applied to the samples from beneath

Permeability testing was conducted on cubic concrete samples measuring 15x15x15 cm, which were cured for 28 days. The test was performed using the apparatus specified in the standard, applying water pressure from beneath the sample and measuring the depth of water penetration into the concrete. Figure 4 illustrates the water pressure applied to the samples from below. Prior to the test, the cubic samples were dried by placing them in an oven at 105°C for 24 hours. Subsequently, they were subjected to water pressure from beneath for a duration of 72 hours [18].

5.2.2 SORPTIVITY TEST

FIG 5. The exposure of the concrete samples to water from beneath

This test was conducted on concrete cylinders with dimensions of 100×50 mm. Three samples from each mixture were examined after the concrete had cured for 28 days. Initially, the test samples were dried at 105°C until they reached a constant weight. The dry samples were then weighed before being immersed in a container filled with water to a depth of 3 mm. The samples were weighed at predetermined intervals to measure the weight increase due to capillary water penetration. Weighing was performed every two hours [19]. The sorptivity (in mm/min1/2^1/21/2) was calculated using Equation 1:

$$^{j} = s \times \sqrt{t} + \alpha \qquad (1)\ [19]$$

In Equation (1), S represents the sorptivity coefficient, ttt denotes time, and α\alphaα is a correction term added to account for surface effects when the specimen is in contact with water (which is often not calculated).

$$^{j} = \Delta m / F \qquad (2)\ [19]$$

Where F represents the sample surface area exposed to water, and Δm is the mass of water absorbed. Figure 5 illustrates the exposure of the concrete samples to water from beneath.

5.2.3 ALKALINITY TEST

To measure the alkalinity of concrete, a solution is prepared by mixing water with finely ground concrete powder. This powder is obtained by grinding a representative sample of concrete into a fine powder to increase its surface area and facilitate dissolution. The ground concrete powder is thoroughly mixed with water to create a homogeneous solution. After preparation, the solution undergoes a filtration process. It is poured onto filter paper placed in a filtration apparatus. The filter paper traps solid particles, while the liquid portion, containing dissolved alkaline compounds from the concrete, passes through. This filtered liquid is collected and separated from the remaining solids. The collected liquid, which contains the dissolved alkaline compounds, is then transferred to a specialized alkalinity measurement device. This device accurately measures the alkalinity of solutions. The liquid sample is introduced into the measurement chamber of the device, where its alkalinity level is quantified. The device provides precise readings, allowing for accurate determination of the alkalinity level in the concrete solution [20]. Finally, the recorded alkalinity measurements are documented for analysis and comparison. Figure 6 illustrates the filtration process for the concrete solution.

FIG 6. The filtration process for the concrete solution

5.2.4 COMPRESSIVE STRENGTH TEST

The compressive strength test involves evaluating concrete specimens with dimensions of 15 × 15 × 15 cm. These samples are typically tested on the 28th day after casting. For each mix used in the study, the average value of three cubes is selected for analysis [21].

5.2.5 TENSILE STRENGTH TEST

A tensile strength test was conducted indirectly using the splitting method on cylindrical concrete specimens measuring 15 × 30 cm. This testing was performed on the 28th day after casting. For each mix used in the study, the average reading of three samples was taken for analysis [22].

6. RESULTS AND DISCUSSION

The results were calculated using the average values for each of the tests: compressive strength, tensile strength, sorptivity, and permeability of the concrete mixes studied in the research. The relationships between the independent variables—compressive strength, tensile strength, sorptivity, and alkalinity—and the dependent variable, permeability, were studied individually.

6.1 SLUMP TEST RESULT

The slump test results for concrete reveal the impact of different materials and their proportions on workability. High-performance concrete with silica (Mix1 and Mix2) shows lower slumps (6 cm and 7 cm) due to silica absorbing water and increasing viscosity, while concrete without silica (Mix3) and the control mix (Mix4) exhibit higher slumps (8 cm), indicating better workability. The Mix5, with a cement content of 350 kg/m³, achieves a slump of 9 cm, reflecting improved workability. Concrete containing slag (Mix6, Mix7, Mix8) shows a gradual increase in slump (9 cm, 10 cm, 11 cm) as slag content increases, and similarly, concrete with fly ash (Mix9, Mix10, Mix11) maintains a slump of 9 cm for Mix9 and Mix10 but increases to 11 cm for F30 due to the spherical shape of fly ash particles. Concrete with silica replacement (Mix12, Mix13, and Mix14) shows lower slumps (7 cm, 7 cm, 6 cm) due to increased viscosity and water absorption. Overall, adding silica reduces slump, while higher slag and fly ash proportions improve workability, and increasing cement content also enhances it.

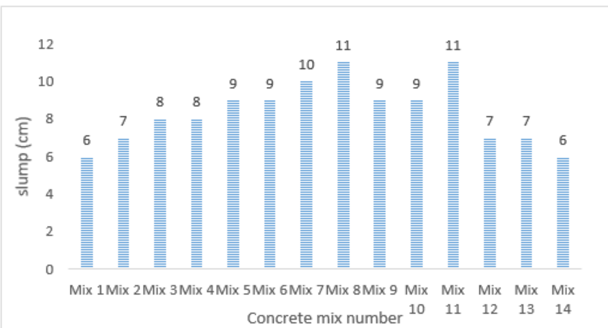

FIG 7. Results of the slump test

6.2 PENETRATION DEPTH AND COMPRESSIVE STRENGTH

Figure 8 illustrates the results of the compressive strength test alongside the penetration depth results. The depicted relationship shows that as compressive strength increases, penetration depth decreases. Specifically, the data indicate that higher compressive resistance corresponds to lower permeability values, as shown. This relationship is logical and can be explained by the fact that as compressive resistance increases, the voids or pores in the material are typically compressed or sealed more effectively. Consequently, this reduces the ability of liquids or gases to pass through the material, resulting in decreased permeability [23] [24] [25] [26] [27].

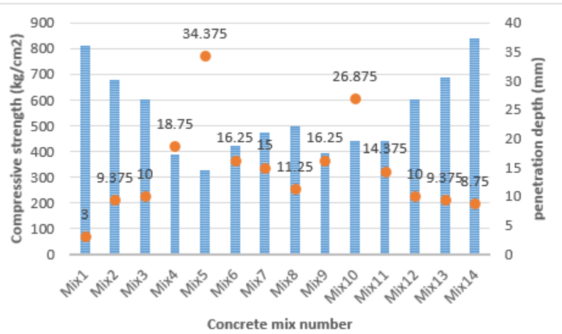

FIG 8. The results of a compressive strength test alongside penetration depth

6.3 PENETRATION DEPTH AND TENSILE STRENGTH

The results depicted in Figure 9 show findings from a tensile strength test alongside penetration depth results. The correlation indicates that as tensile strength increases, permeability decreases. Specifically, the data reveal that higher tensile strength is associated with lower permeability values, as illustrated. This correlation is logical and can be explained by the fact that increased tensile strength reduces the material's permeability, thereby limiting the passage of liquids through it [23] [24] [25] [26].

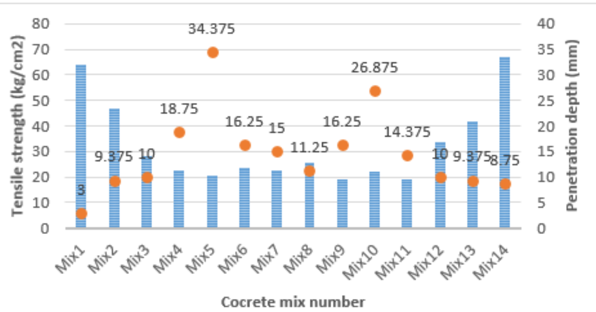

FIG 9. A tensile strength test juxtaposed with penetration depth results

6.4 PERMEABILITY AND SORPTIVITY

The findings suggest that an increase in "concrete sorptivity" tends to correspond with a moderate increase in "concrete permeability." Conversely, if "concrete absorption" decreases, there may be a moderate decrease in "concrete permeability." This relationship is illustrated in Figure 9. The underlying reason for this pattern is that higher concrete sorptivity, indicating faster water absorption, increases the likelihood of water seeping through the concrete, thereby raising its permeability. Conversely, decreasing concrete absorption reduces the probability of water seepage, leading to a decrease in concrete permeability [28] [29] [30].

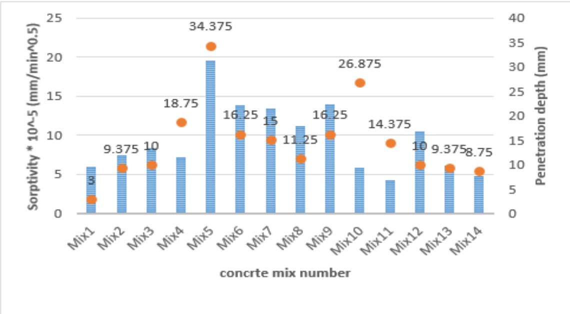

FIG 9. A sorptivity test juxtaposed with penetration depth results

6.5 PERMEABILITY AND ALKALINITY

The results indicate that concrete mixtures with lower permeability exhibit high alkalinity values exceeding 13.5. Conversely, mixtures with higher permeability tend to have alkalinity levels ranging between 12.5 and 13. Additionally, there are mixtures with alkalinity values between 13 and 13.5. This suggests a relationship between alkalinity levels and concrete permeability, where higher alkalinity may enhance resistance to water seepage due to its effects on the concrete structure and its interactions with water and other materials. This relationship is illustrated in Figure 10.

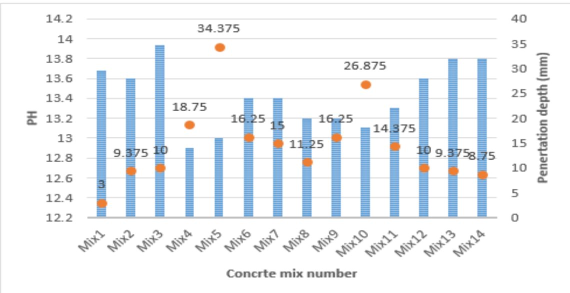

FIG 10. The alkalinity test alongside penetration depth results

6.6 COMPARISON BETWEEN THE USED CEMENTITIOUS MATERIALS

Figure 11 compares the results of concrete mixes where different proportions of cement were replaced with various cementitious materials, against the control mix without any cementitious materials. The findings indicate that the mixes with the lowest permeability were those in the silica group, followed by the slag group, and then the fly ash group.

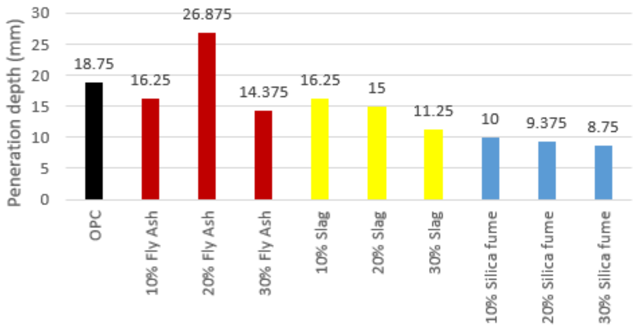

FIG 11. Comparison between the used cementitious materials

The observed results can be attributed to the distinct characteristics of the different cementitious materials used as substitutes for cement in the concrete mixes. Silica fume, for instance, is highly reactive and effectively fills voids within the concrete matrix, resulting in a denser and less permeable concrete. Slag, with its pozzolanic properties, enhances the binding of concrete particles, thus improving the durability and reducing permeability. Fly ash, also a pozzolan, enhances concrete's workability, strength, and durability. Therefore, the lower permeability observed in mixes containing silica fume, followed by slag and fly ash, is due to the specific properties of these materials. They contribute to creating denser and more tightly packed concrete structures, thereby reducing permeability [31] [32].

7. PERMEABILITY PREDICTION MODEL

A predictive model for concrete permeability was developed using SPSS Statistics 28, a statistical computing software utilized for data analysis. In this model, concrete penetration depth was considered the dependent variable, while compressive strength, tensile strength, absorptivity, alkalinity, binder content, and water-cement ratio served as independent variables. The model assumed that all variables were measured on a continuous scale, except for alkalinity, which was measured on a nominal scale. In this nominal scale, alkalinity values were categorized as follows: values ranging from 12.5 to 13 were assigned a value of 1, values between 13.1 and 13.5 were assigned a value of 2, and values from 13.6 to 14 were assigned a value of 3. Fourteen data points were input for each variable.

7.1 CORRELATIONS

Table 3 presents the Pearson correlation values, their significance (Sig.), and the number of valid cases for each variable. The table displays the correlation coefficients, which quantify the degree of association between the variables. It also indicates whether the relationship is positive or negative and provides insights into the strength of these relationships.

TABLE 3. Pearson Correlations

	Penetration depth	Water cement ratio	Binder content	Alkalinity	Sorptivity	Tensile strength	Compressive strength
Penetration depth	Pearson correlation						
	1	.756**	-.753**	-.800**	.547*	-.644*	-.785**
	Sig. (2-tailed)						
		0.002	0.002	0.001	0.043	0.013	0.001
	N						
	14	14	14	14	14	14	14

The correlation values reveal the relationship between permeability and each of the following variables: compressive strength, tensile strength, sorptivity, alkalinity, binder content, and water-to-cement ratio. These relationships vary, showing both direct (positive) and inverse (negative) associations.

7.2 THE DEVELOPED PERMEABILITY MODEL

As illustrated by Equation 3, our developed model is a linear equation that relates the dependent variable, concrete permeability, to the independent variables: compressive strength, tensile strength, sorptivity, alkalinity, binder content, and water-to-cement ratio.

$$P = -0.085\ CS + 0.338\ TS - 0.606\ S + 4.907\ K\ (1, 2, 3) - 0.021\ BC + 77.285\ WCR + 29.953 \quad (3)$$

Where (P) represents the water penetration depth in mm, (CS) denotes compressive strength in Kg/cm², (TS) denotes tensile strength in Kg/cm², (S) denotes sorptivity divided by (10^{-5}) in mm/sec^{0.5}), K) is a constant taking the value of 1 when alkalinity ranges from 12.5 to 13, 2 when alkalinity ranges from greater than 13 to 13.5, and 3 when alkalinity ranges from greater than 13.5 to 14, (BC) represents concrete binder content in Kg/m³, and (WCR) represents the water cement ratio.

The R-squared value of 0.861 in a linear regression analysis between concrete permeability (dependent variable) and sex independent variables - compressive strength, tensile strength, absorptivity, alkalinity, binder content, and water cement ratio - indicates that approximately 86.1% of the variance in concrete permeability can be explained by the variation in these independent variables. This high R-squared value suggests a strong statistical relationship between the dependent and independent variables. It's worth mentioning that the significance level for the model is 0.01, this provides evidence for rejecting the null hypothesis, which typically assumes that there is no relationship between the variables under study.

7.3 THE DEVELOPED SORPTIVITY MODEL

By utilizing the correlation coefficient from Table 2, we observe a correlation between sorptivity, compressive strength, binder content, and water cement ratio. Assuming that sorptivity is the dependent variable and compressive strength, binder content, and water cement ratio are independent variables, we can obtain the equation 4 using a linear regression analysis.

$$S = -0.01\ CS + 0.003\ BC + 38.114\ WCR + 2.125 \quad (4)$$

Where (S) denotes sorptivity divided to (10^ {-5}) in mm/min^ {0.5}), (CS) denotes compressive strength in Kg/cm², (BC) represents concrete binder content in Kg/m³, and (WCR) represents the water cement ratio. The statistical analysis yielded the following results: (R square = 0.642) and (sig. = 0.04).

7.4 THE DEVELOPED ALKALINITY MODEL

Using the same statistical tool, a linear regression equation was derived between the alkalinity range (as the dependent variable) and compressive strength, binder content, and water-to-cement ratio (as independent variables). This regression equation is presented in Equation 5.

$$K = 0.003\ CS + 0.001\ BC - 2.611\ WCR + 0.63 \quad (5)$$

Where (K) is a constant denotes alkalinity range, (CS) denotes compressive strength in Kg/cm², (BC) represents concrete binder content in Kg/m³, and (WCR) represents the water cement ratio. The statistical analysis yielded the following results: (R square = 0.817) and (sig. = 0.001).

8. MODEL VALIDATION

To evaluate the accuracy of the proposed model, we compared its predictions with experimental data from five different published studies. This comparison involved applying the proposed model to the experimental data from these studies and assessing how closely the model's predictions aligned with the actual values reported in the literature. This approach provided a robust validation of the model's performance and demonstrated its reliability in replicating the observed outcomes from these studies. The validation was conducted using the Mean Percentage Error (MPE). MPE is a metric used to assess the accuracy of forecasts or predictions. It calculates the average difference between predicted values and actual values, expressed as a percentage of the actual values. Equation 6 illustrates the formula for the Mean Percentage Error [33] [34].

$$\text{MPE} = f(x) = \frac{1}{n}\sum_{i=1}^{n} \frac{(Y\_i - \hat{Y}\_i)}{Y\_i} \times 100 \qquad (6)\ [33]\ [34]$$

Where:
- n is the number of observations.
- Y_i is the actual value.
- Ŷ_i is the forecasted or predicted value.

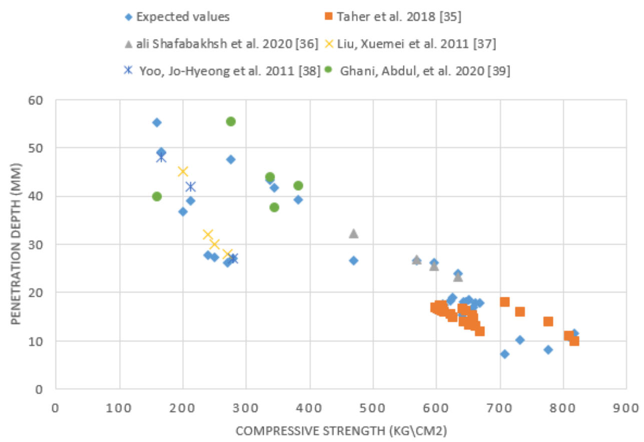

Fig 12. The comparison between the predicted values generated by the proposed models and their actual experimental values.

The Mean Percentage Error (MPE) for the dataset is approximately -1.62%, and when considering the absolute value, it is around 1.62%. This indicates that the proposed model is highly accurate, with predictions deviating from the actual values by an average of only 1.62%. Despite a slight tendency for underestimation, this small deviation does not significantly impact the overall accuracy, making the model reliable and precise in its predictions.

9. COMPARISON OF THE DEVELOPED MODELS WITH MODELS FROM OTHER STUDIES.

In this study, we developed a model based on a regression equation to predict water penetration depth, focusing on variables such as compressive strength, tensile strength, sorptivity, alkalinity, binder content, and water-cement ratio. This model offers simplicity and ease of application using directly measurable variables, evaluating linear relationships between variables and water penetration depth.

In contrast, the model of (Li, Xinxin et al. 2019) utilizes a 3D Finite Element Method (FEM) based on the HYMOSTRUC3D model to simulate water flow through cement paste microstructures. This model is complex and requires advanced modeling and accurate microstructural data but provides higher precision in understanding structural impacts and time-dependent changes [40].

The model of (Park, Sang-Soon, et al. 2012) combines experimental data and numerical modeling to assess early-age concrete behavior, focusing on crack formation. This model requires both experimental data and numerical modeling, making it of moderate complexity. It integrates early-age cracking effects and numerical simulations for a comprehensive understanding [41].

On the other hand, the model of (Ahmad, Shamsad, et al. 2008) uses regression models to relate water penetration depth to the chloride diffusion coefficient and permeability, with a focus on practical applications using easily obtainable concrete properties. This model offers a straightforward approach to determining diffusion and permeability using mix design parameters [42].

Overall, while our model provides a simpler application approach, the other models offer varying levels of detail and precision, from advanced FEM modeling to practical regression-based models.

Table 4. Comparison of the developed models with models from other studies.

Criterion	Model of our Study	Model of (Li, Xinxin et al. 2019) [40]	Model of (Park, Sang-Soon, et al. 2012) [41]	Model of (Ahmad, Shamsad, et al. 2008) [42]
Mathematical Structure	Regression equation	Utilizes a 3D Finite Element Method (FEM) based on the HYMOSTRUC3D model to simulate water flow through cement paste microstructures	Combines experimental data and numerical modeling to consider early-age concrete behavior, especially crack formation.	Utilizes regression models to relate the depth of water penetration to the coefficient of chloride diffusion and permeability.
Variables Used	• Compressive Strength • Tensile • Strength • Sorptivity • Alkalinity	• Water-Cement Ratio • Curing Age Degree of Hydration • Microstructural Properties	• Crack Width • Degree of Saturation • Porosity • Water-Cement	• Water-Cement Ratio (W/C) • Cement Type • Cement Content.

	• Binder Content • Water-Cement Ratio	(pore structure).	Ratio (WCR).	
Relation to Water Penetration Depth	Linear relationships between variables and water penetration depth.	Simulates detailed pore-scale flow and permeability evolution, focusing on hydration processes and microstructural effects.	Emphasizes the influence of crack width and early-age properties on water penetration.	Relates water penetration depth to chloride diffusion coefficient, emphasizing the effect of cement type and content.
Ease of Application	Simple to apply with directly measurable variables.	Complex and requires advanced modeling and accurate microstructural data, but offers higher precision.	Requires both experimental data and numerical modeling, focusing on early-age cracking; moderate complexity.	Straightforward application using regression equations based on mix design parameters.
Advantages	Simplicity of the model and ease of use.	Provides an in-depth understanding of microstructural impacts and time-dependent changes.	Integrates early-age cracking effects and numerical simulations for a comprehensive understanding.	Offers practical utility in determining diffusion and permeability using easily obtainable concrete properties.

Conclusion

This study successfully developed a predictive model for estimating water penetration depth in concrete using linear regression analysis via SPSS, based on key properties such as compressive strength, tensile strength, sorptivity, alkalinity, binder content, and water-cement ratio. The following conclusions were drawn:

- The model demonstrated high accuracy in predicting water penetration depth, supported by a Mean Percentage Error (MPE) of 1.64%.
- Higher compressive and tensile strengths reduce concrete permeability, enhancing its resistance to water.
- Higher sorptivity is associated with increased permeability, indicating that concrete with higher sorptivity is more susceptible to water penetration.
- Higher alkalinity values are linked to lower permeability, suggesting that an alkaline environment improves concrete's resistance to water penetration.
- Mixtures containing silica fume showed the lowest water penetration depth, making them the most effective in reducing permeability.
- Mixtures containing slag also performed well in reducing permeability, followed by those containing fly ash.
- The model is characterized by ease of application and simplicity, making it a valuable tool for engineers in improving concrete mix designs.

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