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Evaluating the Mechanical Properties of Polymer Concrete a Comparative Study of Various Polymeric Additives

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Abstract

Evaluating the Mechanical Properties of Polymer Concrete: A Comparative Study of Various Polymeric Additives examines the impact of different polymeric additives on the mechanical properties of polymer concrete, a composite material that combines traditional concrete with polymers to enhance its performance. This area of study has gained traction in civil engineering and construction due to the superior mechanical properties and durability of polymer concrete compared to conventional concrete, making it an attractive option for various applications, including 3D printing and infrastructure projects.[1.[۲][

This research primarily focuses on how polymer additives, such as polyvinyl alcohol (PVA) and vinyl acetate–ethylene copolymer (VAE), influence the compressive, flexural, and tensile strength of the concrete, as well as its workability and resistance to environmental factors. Key findings reveal that specific polymers can significantly improve the mechanical performance of concrete, with certain combinations yielding up to 33% increases in compressive strength and 63% in flexural strength after 28 days of curing.[3] Conversely, the study also highlights potential drawbacks, such as the adverse effects of excessive polymer content on hydration and structural integrity, necessitating careful optimization of mixture formulations.[1.[۴][

The methodology employed in the study includes a three-level two-factor experimental design, which facilitates a systematic assessment of various material combinations. Results are analyzed through rigorous statistical techniques, including regression analysis, to quantify the influences of polymer types and proportions on concrete properties. The outcomes emphasize the dynamic relationship between polymer content and performance metrics, providing insights for future applications in construction and material science.[4.[۱][

Notably, this research addresses significant controversies surrounding the use of polymer additives, particularly concerns about their potential to hinder hydration if used excessively. This emphasizes the need for balanced formulations to maximize the benefits of polymer modifications while mitigating any negative impacts on concrete strength and durability.[1][4]. As the construction industry increasingly seeks materials that combine performance with sustainability, understanding the mechanical properties of polymer concrete remains a critical area of investigation.

Keywords: Mechanical Properties Polymer Concrete ،engineering and construction

Introduction

Polymer concrete, a composite material formed by combining traditional concrete with polymeric additives, has garnered significant attention due to its enhanced mechanical properties and durability compared to conventional concrete. The incorporation of polymers, such as polyvinyl alcohol (PVA), into the cement matrix has been shown to improve various characteristics of the resulting material, including compressive, flexural, and tensile strength, as well as resistance to environmental factors and cracking[1][2].

The effects of polymer additives on microstructural changes within the concrete matrix are noteworthy. Studies utilizing Scanning Electron Microscopy (SEM) reveal that the addition of PVA facilitates the formation of a three-dimensional network that enhances crack-filling capabilities and reduces porosity, provided that the polymer is used in moderation. However, excessive amounts of PVA can hinder hydration by forming a film over the particles, which may compromise the structural integrity of the concrete[1][5].

Moreover, the introduction of polymers significantly influences water retention characteristics, essential for maintaining moisture during the curing process. While moderate polymer content aids in this aspect, higher concentrations may lead to the formation of expanded air voids, ultimately reducing the density of the concrete due to poor mixing characteristics[1][6].

Recent experimental studies have investigated polymer-modified concrete and mortar, emphasizing the role of various polymer types and their ratios in the mix design. These studies typically utilize Portland cement and aggregates such as inert lava, with findings indicating that the appropriate use of polymers can result in materials capable of achieving maximum strength without visible surface cracking. The research highlights the importance of considering factors like cement type, aggregate characteristics, workability during casting, and environmental conditions to optimize the performance of polymer-modified mixtures[1][7].

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Methodology

Experimental Design

In this study, a three-level two-factor experimental design was employed to assess the mechanical properties of concrete containing polymer additives. The experimental framework was organized to analyze the combined effects of fly ash and vinyl acetate–ethylene copolymer on concrete suitable for 3D printing, optimizing the volume of experimental work while meeting statistical requirements[4][1].

The experiments were planned using a typical matrix, which provided a systematic approach for evaluating various combinations of material proportions and additives. The setting time, defined as the duration from mixing until the concrete begins to set, was measured in accordance with EN 196-3 standards[4].

Materials

The primary materials utilized in this research included Portland cement (CEM I
42.5R) sourced from the Dyckerhoff plant in Ukraine and fly ash derived from the Burshtynska thermal power plant. The fly ash classified as type II (category B) demonstrated a sieve residue of no more than 25% on a 45 ¼m mesh, complying with EN 450-1:2012 standards[4]. The chemical and mineralogical compositions of both the Portland cement and fly ash were documented to ensure the correct formulation of the mixtures[4].

Polymer additives were selected based on their potential impact on concrete properties. The studied redispersed polymer powders included vinyl ester of versatile acid (VEOVA), copolymer vinyl acetate–ethylene (VAE), and polymer of vinyl acetate (PVA)[1].

Mixture Proportions and Experimental Setup

The concrete mixtures were prepared with varying proportions of redispersed polymer powders (0%, 1.0%, and 2.0% by weight of the dry mix), while maintaining a constant water-to-cement (W/C) ratio of 0.6. Each mixture included quartz sand as aggregate and was supplemented with a polycarboxylate superplasticizer and a hardening accelerator (sodium sulfate, Na2SO4)[4][1].

During the mixing process, the properties of the mixtures were meticulously recorded. The workability was assessed using the standard cone method, while the tensile splitting strength and compressive strength were determined at specified curing ages of 1, 7, and 28 days, following the guidelines of EN 196-1[1].

Testing Procedures

After casting, the specimens were demoulded after 1-2 days and cured under conditions of 95% humidity[1]. The tensile splitting strength tests were conducted using a testing machine (FP-100/1 100 kN), applying cylindrical steel heads at the sample boundaries until failure occurred at a constant loading rate of 50 N/s. Compressive strength tests involved applying load at a speed of 500 N/s on samples until they reached failure[4][1].

The analysis included the development of quadratic regression equations to quantify the individual and combined influences of various factors on the concrete properties, providing insights into the optimal formulation for achieving desired structural characteristics[4][1]. Graphical dependencies illustrating the interaction effects of composition factors on the properties of concrete suitable for 3D printing were also generated to facilitate the understanding of the experimental outcomes[4].

An ITS test was conducted to determine the tensile strength of neat and polymermodified asphalt mixtures according to AASHTO-T283 using an indirect tensile compression tester. The test was also conducted on wet conditioned samples to determine how sensitive the mixture was to moisture damage. Six specimens were fabricated for each mixture: three in dry condition and three in wet condition. The wet conditioning was performed by submerging samples in a water bath at a temperature of 60 ±

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1 ˚C for 24 h and then at ambient temperature (25 ± 0.5 ˚C) for 2 h. Following that, a constant deformation rate of 50 mm/min is applied in the diametral direction of the specimen. To determine the tensile strength, the load at failure was recorded, as shown below. The load at failure was recorded and used to calculate the tensile strength as follows:

$$S_t = \frac{2P}{\pi \times T \times D} \quad (1)$$

where *St* is the tensile strength (MPa), *P* is the maximum load (N), *T* is the sample thickness (mm), *D* is the sample diameter (mm).
Finally, the tensile strength ratio (*TSR*) was determined using the following equation:

$$TSR = \frac{\text{Tensile strength of wet condition}}{\text{Tensile strength of dry condition}} * 100 \quad (2)$$

A higher *TSR* value indicates that the asphalt mix will have better resistance to moisture damage. The *TSR* must be greater than 80% as recommended by AASHTO T 283 and the Ministry of Transportation.

4.5. Comparison and Overall Ranking of PMA Mixture Performance

4.5.1. Pair Comparison

To compare the different mixtures pair, the “effect size method” was implemented in this research instead of statistical tests for significance (*t*-test and ANOVA), which were not applicable due to the limited number of data points for the experimental results. Therefore, the results of the statistical test might be misleading [65]. However, based on the difference in the means of the two groups and the standard deviation, the effect size value (*d*) can be determined by the following equation:

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$$d = \frac{|\bar{x}_t - \bar{x}_r|}{\sqrt{\frac{(n_t-1)s_t^2+(n_r-1)s_r^2}{(n_t+n_r)}}} \quad (3)$$

where $\bar{x}_t$ is the mean of treatment group, $\bar{x}_r$ is the mean of the reference group, n_t is the number of samples in the treatment group, n_r is the number of samples in the reference group, s_t is the standard deviation of the treatment group, s_r is the standard deviation of the reference group.

4.5.2. Overall Ranking

In order to decide which mix design had better performance, all different mixes were ranked based on a 6-point scale. This could help select the best mix design by each of the asphalt mixture performances, where the mixture with the best performance would be ranked 1 and the mixture with the least (worst) performance would have the highest number. Based on the asphalt mixture performances for the selected asphalt mixtures analyzed in this study, the relative significance of each mix design's overall rank can be determined using the Relative Importance Index (*RII*) method. The *RII* is computed as:

$$\mathbf{RII} = \sum \frac{1 + A - W}{A * N} \quad \mathbf{(4)}$$

where *A* is the highest weight = 6; *W* is the weight given to each performance test and ranges from 1 to 6; and *N* the total number of performance tests.

5. Results and Discussions

5.1. Dynamic Modulus Result

The experimental data of dynamic modulus (|E*|) and phase angle (δ) versus frequency at different temperatures for different modified asphalt mixtures are presented in Figures 8 and 9, respectively.

Generally, the dynamic moduli values of all modified asphalt mixtures increased by decreasing the temperature, and they were increased by increasing the frequency. While phase angle increased by increasing the

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temperature, it was decreased by increasing the frequency. This is because as the temperature increases or decreases, the viscosity of the asphalt binder changes, which in turn causes a change in the elasticity of asphalt mixtures. In addition, it is also found that all asphalt mixtures showed similar trends regardless of modifier types. According to many studies [27,42,43,46,66–70], polymer modification resulted in a higher modulus for the modified asphalt mixture as compared with the control asphalt mixture. In this study, similar behavior was found by using different polymers, where the dynamic modulus of asphalt mixtures improved due to polymer addition.

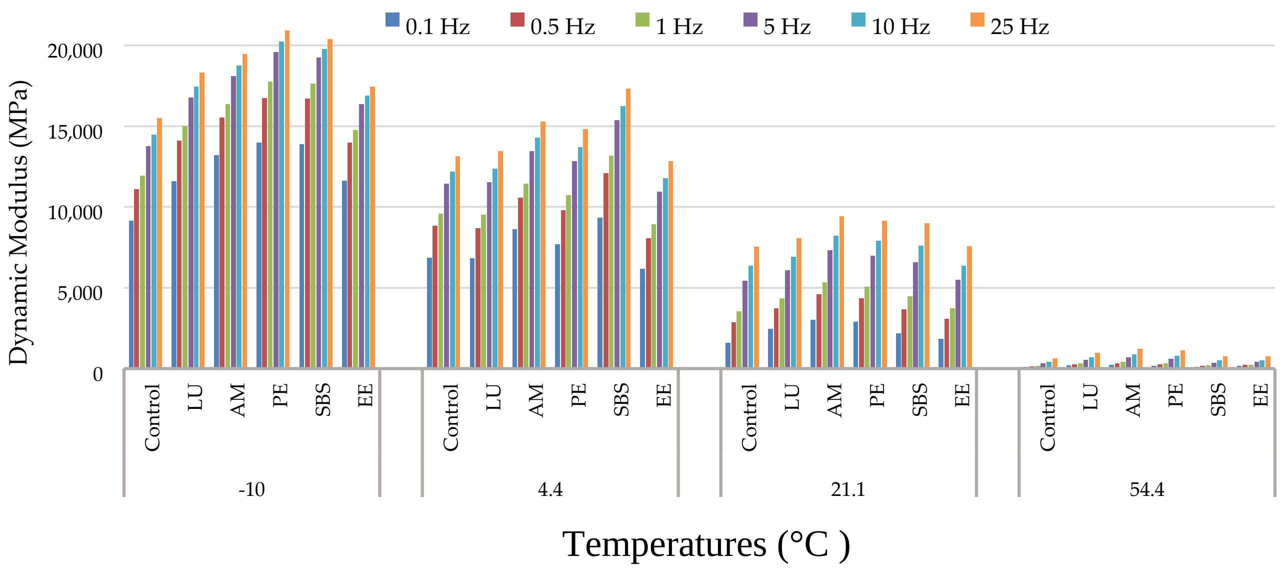

Figure 8. Dynamic modulus versus frequencies at different temperature.

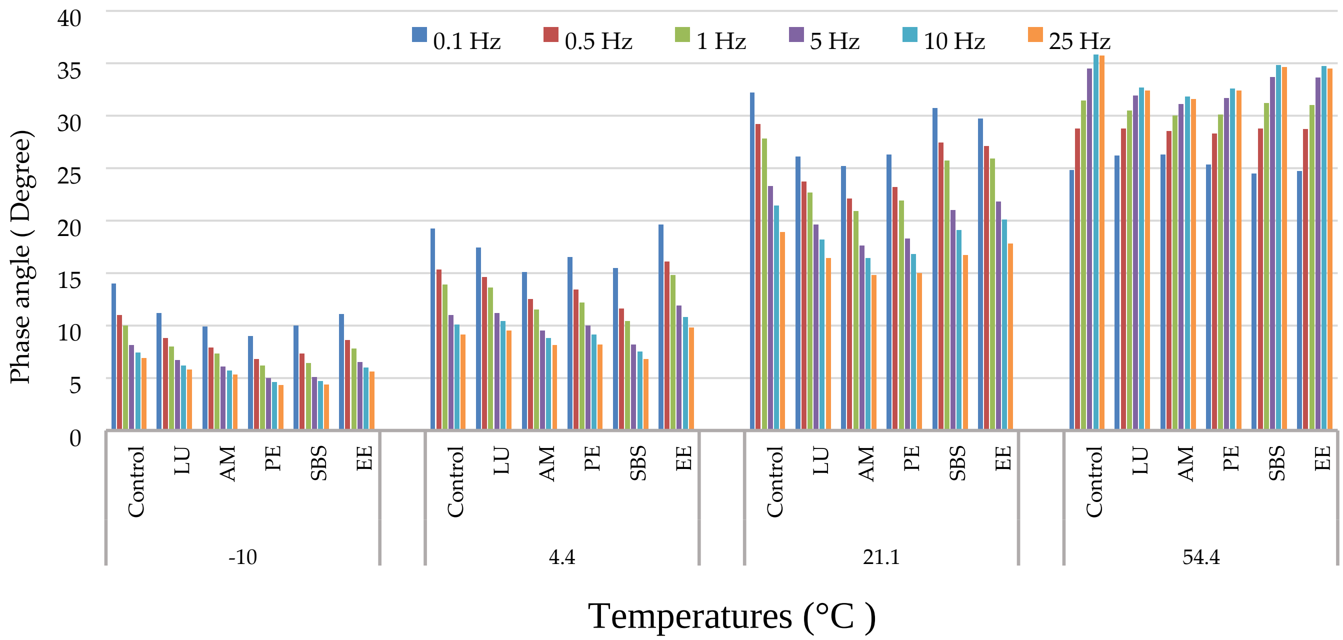

Figure 9. Phase angle versus frequencies at different temperatures.

Based on the difference in the means of the two groups and the standard deviation, the effect size values (d) were calculated for different asphalt mixture performance tests, as shown in Tables 8–11. Based on the literature, an effect size of 1.6 was used in this study to determine the effect of differences in dynamic modulus values of asphalt mixtures on the performance properties [65]. Effect sizes with values less than 1.6 indicate no difference in dynamic modulus values of the two asphalt mixtures. Table 8 presents the effect size values at the temperature of −10 °C; the results show that the Lucolast mixture had statistically no difference (0.26) in dynamic modulus compared with the EE-2 mixture. Additionally, the Paveflex mixture had statistically no difference (0.57) compared with the SBS mixture.

Table 8. Effect sizes dynamic modulus at the

	NEAT	LU	AM	PF	SBS	EE
NEAT	-	4.96	6.04	9.01	9.52	2.66
LU	4.96	-	2.81	8.15	9.48	0.26
AM	6.04	2.81	-	2.66	3.15	1.62
PF	9.01	8.15	2.66	-	0.57	3.21
SBS	9.52	9.48	3.15	0.57	-	3.47
EE	2.66	0.26	1.62	3.21	3.47	-

Table 9. Effect sizes dynamic modulus at the temperature of 4.4 °C.

	NEAT	LU	AM	PF	SBS	EE
NEAT	-	1.11	7.09	3.59	99.74	2.16
LU	1.11	-	7.21	3.74	63.32	1.93
AM	7.09	7.21	-	1.75	6.47	6.30
PF	3.59	3.74	1.75	-	7.61	4.10
SBS	99.74	63.32	6.47	7.61	-	13.95
EE	2.16	1.93	6.30	4.10	13.95	-

temperature of −10 °C.

	NEAT	LU	AM	PF	SBS	EE
NEAT	-	5.00	7.64	10.38	5.75	0.83
LU	5.00	-	5.17	11.48	1.01	3.92
AM	7.64	5.17	-	1.62	4.95	6.92
PF	10.38	11.48	1.62	-	16.62	9.20
SBS	5.75	1.01	4.95	16.62	-	4.62
EE	0.83	3.92	6.92	9.20	4.62	-

Table 11. Effect sizes dynamic modulus at the temperature of 54.4 °C.

	NEAT	LU	AM	PF	SBS	EE
NEAT	-	6.58	11.80	8.83	2.76	4.09

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LU	6.58	-	3.03	0.42	5.45	2.84
AM	11.80	3.03	-	2.96	10.43	6.55
PF	8.83	0.42	2.96	-	7.35	3.75
SBS	2.76	5.45	10.43	7.35	-	2.65
EE	4.09	2.84	6.55	3.75	2.65	-

Table 10. Effect sizes dynamic modulus at the temperature of 21.1 ˚C.

Table 9 shows the effect sizes for the dynamic modulus of different mixtures at 4.4 ˚C. It shows that the differences are statistically significant between all asphalt mixtures since the effect size values obtained were greater than 1.6 except for the mixture with Lucolast corresponding to the control mixture.

For a temperature of 21 ˚C, the results of which are tabulated in Table 10, the control mixture had statistically no difference (0.85) in dynamic modulus compared with the EE-2 mixture. Additionally, the Lucolast mixture had statistically no difference (1.01) compared with the SBS mixture.

Table 11 provides the effect size values at temperature of 54.4 ˚C, where only the mixture with Lucolast had no difference in dynamic modulus compared with the Paveflex mixture since the effect size values obtained were less than 1.6.

5.2. Flow Number (Fn) Result

Based on the test findings, all asphalt mixtures reached the failure stage with a cumulative permanent strain of 50,000 microstrains. Figure 10 illustrates the cumulative permanent strain curves of different asphalt mixtures. A significant variance was noticed between control and all modified asphalt mixtures. Thus, all mixtures with PMA demonstrated lower permanent strain than the control mixture. This is attributed to the presence of polymer material in the asphalt binder, which can increase the adherence of mixture components, resulting in increased mixture strength.

The Fn and final load cycle of asphalt mixtures are presented in Table 12. Asphalt mixture modified with Lucolast7010 displayed a higher Fn value (182) and reached the failure stage after 432 cycles, followed by the mixture containing Anglomk2144, which showed Fn 120 and reached the failure stage after 336 cycles.

Table 13 provides the effect sizes for the Fn test of different mixtures. It shows that the differences in Fn values are statistically significant between all asphalt mixtures since the effect size values obtained are greater than 1.6.

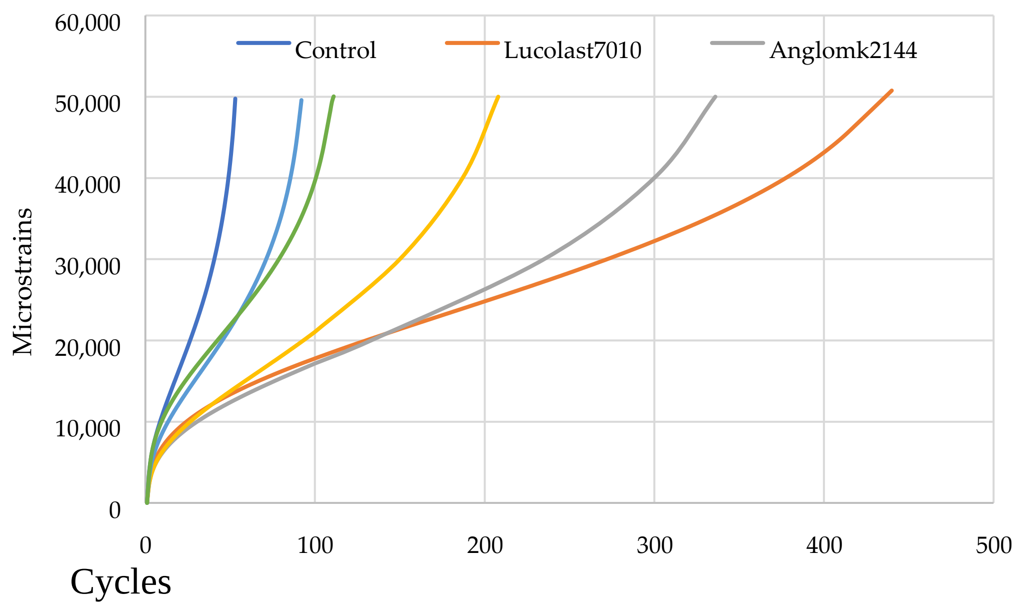

Figure 10. Cumulative permanent strain curves for different mixtures.

Asphalt Mixture	Fn		Failure	
	Cycles	Strain	Cycles	Strain
Control	25	19,683	66	52,377
Lucolast7010	182	23,652	432	50,184
Anglomk2144	120	18,982	336	50,292
Paveflex140	93	20,209	244	50,058
SBS KTR401	33	16,811	93	52,246
EE-2	46	21,338	114	51,111

Table 13. Effect sizes of Fn.

NEAT	LU	AM	PF	SBS	EE

NEAT	-	7.54	8.29	17.86	2.22	5.09
LU	7.54	-	2.65	4.33	7.26	6.60
AM	8.29	2.65	-	2.49	7.97	6.67
PF	17.86	4.33	2.49	-	37.95	18.43
SBS	2.22	7.26	7.97	37.95	-	5.81
EE	5.09	6.60	6.67	18.43	5.81	-

Table 12. Flow number test data for different mixtures.

5.3. Hamburg Wheel Tracking Result

The test was used to evaluate rutting and to determine the failure susceptibility because of weak adhesion between the binder and aggregates. Before testing, the specimens were submerged underwater for 60 min at a temperature of 50 °C. All specimens were tested at 52 pass/minute. The specimen's rut depth and the number of passes were recorded. Testing ended when the rut depth reached 12.0 mm or 20,000 passes, whichever came first. Figure 11 presents the average rut depth recorded with the number of passes for all the mixtures. It is observed that the PMA mixtures had lower moisture sustainability than the neat asphalt mixture. From the figure, the asphalt mix modified with EE-2 ranked as the best mixture, followed by Anglomak2144, Paveflax140, Lucolast7010, and SBS KTR401.

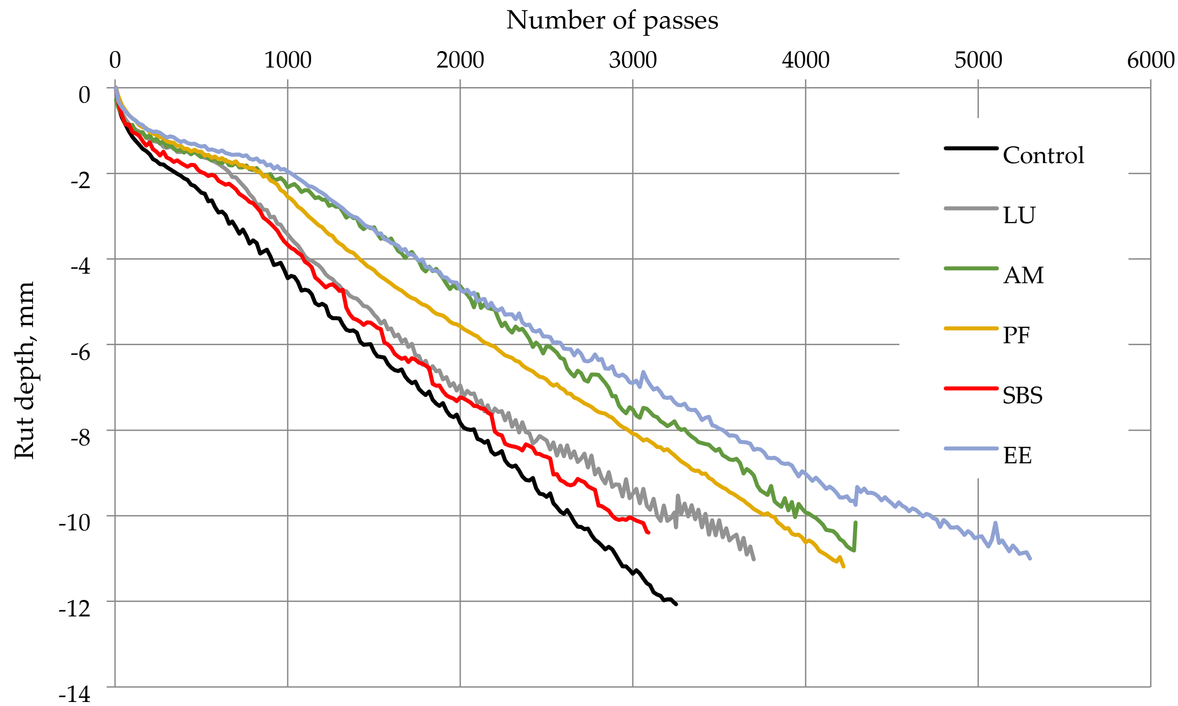

Figure 11. Rut depth versus the number of passes for different mixtures.

Results

The results of the study on polymer concrete revealed significant variations in mechanical properties based on the type and amount of polymeric additives used. Notably, as curing time increased, the failure modes of the polymer concrete matrix (PCM) samples transitioned from mortar failure to interface failure, indicating enhanced bonding characteristics over time[3].

Compressive and Flexural Strength

The PCM sample containing ethylene-vinyl acetate (EVA) demonstrated the most favorable performance, exhibiting increases of up to 33% in compressive strength and 63% in flexural strength after 28 days of curing compared to control samples[3]. Additionally, the experimental results showed that replacing traditional components with polymer additives generally improved internal bond strength and bending stiffness, while also reducing water absorption and thickness swelling in composite boards[8][9].

Workability and Setting Time

The introduction of redispersed polymer powder (RPP) notably enhanced the workability of the concrete mixtures, with measurements of cone immersion increasing from 8 cm to a range of 10–11.5 cm at a constant water and polymer content of 1% by weight[4]. As the RPP content increased to 2%, further improvements in workability were observed, reaching 12–13.5 cm[4]. However, the impact of RPP on structural strength was complex; while a medium content (1%) of vinyl acetate–ethylene copolymer showed beneficial effects, higher concentrations resulted in decreased strength[4].

Statistical Analysis

The regression analysis of the various mixtures indicated that the setting time, compressive strength, and tensile splitting strength were significantly influenced by the composition of the concrete mixtures. Quadratic regression equations derived from the experimental data effectively illustrated the individual and combined influences of factors such as polymer content on the mechanical properties of the concrete[4]. The analysis highlighted the importance of optimizing the mixture composition to achieve superior mechanical performance.

Discussion

The research into polymer concrete has revealed significant insights into the impact of various polymeric additives on the mechanical properties of concrete mixtures. The addition of redispersible polymer powders (RPP) has been shown to influence both the setting time and structural integrity of concrete. Specifically, incorporating RPP can extend the setting time, enhancing the “printing window” for 3D printing applications by 8–15%[4]. However, this benefit comes at a cost; excessive RPP content negatively affects compressive and tensile splitting strength, particularly at early curing stages[4].

In evaluating the influence of polymer content, the results indicate that while RPP reduces initial strength, it can enhance performance over time, particularly at 28 days of curing[4]. This temporal dynamic is critical for applications where delayed strength gain is acceptable or even desirable. The positive effect on tensile splitting strength—ranging from 35–65% with increased RPP content—highlights the potential of these materials for long-term structural applications[4]. Moreover, the comparative analysis reveals that the presence of copolymers, such as vinyl acetate–ethylene, yields superior mechanical properties, suggesting a preference for specific polymer types in formulation designs[4].

The interplay between RPP and other additives, like calcium alginate-based (CAB) materials, is particularly noteworthy. Increased CAB concentrations correlate with enhanced structural strength, achieving a significant rise of 12–15%[4]. However, the reduction in structural strength due to high RPP content—estimated at 8–10%—emphasizes the need for careful optimization in mixture formulations[4]. This optimization process is essential to harness the strengths of both RPP and CAB while mitigating their individual weaknesses, particularly in the context of 3D printing, where material properties can directly impact the efficiency of the printing process and the quality of the final product[4].

The study also highlights the importance of statistical analysis in understanding the influence of multiple factors on concrete properties. The use of regression equations has proven invaluable for establishing relationships between independent variables—such as polymer type and concentration—and performance metrics like compressive and tensile strength[4]. The linear nature of some interactions further simplifies the modeling process, allowing for straightforward predictions and optimizations in material formulation.

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