



Modeling the Influence of Modification with Coal Fly Ash and Silica Fumes Additives on [Permanent Deformation (PD)- Fatigue Life (FL)] Relationship of Asphalt Concrete (AC)

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Keywords

Asphalt,
Modeling,
Silica fumes (SF),
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Dynamic flexure,
Fatigue life (FL),
Permanent Deformation (PD).

Abstract

Asphalt concrete (AC) pavements usually experience cumulative permanent deformation (PD) under the dynamic loading of vehicles. Implementation of additives could be beneficial in controlling permanent deformation (PD) and extending fatigue life (FL). In the present investigation, control and modified AC mixtures slab samples were prepared at optimum binder (OB) requirement with the aid of roller compaction. Silica fumes (SF) and coal fly ash (CFA) were implemented as additives for partial replacement of binder and mineral filler respectively. Beam specimens were extruded from the slab samples and subjected to dynamic flexural fatigue (DFF) with the aid of four points beam bending (FPBB) apparatus. The test was conducted at 20 °C environment and three constant strain levels (CSL) of (250, 400, and 750) microstrain. Data of (PD) and (FL) were analyzed. It was observed that implementation of 4 % of CFA into the AC mixture had clearly extended the FL. After 10000 repetitions of DFF, the PD of the mixtures was (0.19, and 0.21) mm for 2 % SF treated, and 4 % CFA treated AC mixtures respectively. The FL was extended by (100, and 200) % after digesting AC with (2 % SF) and (4 % CFA) respectively representing the best content when compared with the control mixture. The obtained mathematical power regression models with high coefficient of determination (0.999 and 0.996) are recommended and may be implemented for fast and preliminary prediction of the influence of additives on PD-FL of AC within the investigated material ranges and instant detection of AC quality.

1. Introduction

Most of the biproducts and waste materials exhibit significant potential as sustainable additives or fillers in AC mixtures. However, its influence on the overall physical and mechanical performance and the mechanisms responsible for enhancing the required strength improvements remain insufficiently understood. Radwan et al., 2026, [1] investigated the influence of CFA on the behavior of AC mixtures and provides chemical and microstructural characterization to explain its behavior. It was observed that CFA improved AC performance. Marshall stiffness (MS) increased by 63 %, and rut depth (RD) declined by 24 %. The resilient modulus (RM) and creep stiffness (CS) increased significantly, indicating enhanced stiffness and resistance to PD. It was concluded that such improvements were attributed to CFA fine particles, which densify the AC matrix and enhance filler-binder interaction. CFA was recommended as sustainable and effective filler for improving AC mixture performance.

Ergeshov et al., 2026, [2] investigated the impact of replacement of SF with CFA in geopolymer mortars. The replacement ratios of SF were (10, 8, 6, 4, and 2) % on a mass basis. According to test results, optimum replacement ratio of SF (4 to 2) % with CFA showed better performance than that of reference mortar in terms of environmental impact categories and strength properties. Such results indicate that SF replacement within this range enhances maintaining structural integrity. Sarir et al., 2025, [3] investigated the influence of CFA on AC mixture performance. The chemical composition and surface texture were analyzed. AC mixtures with filler contents of (6, 4.5, and 3) % were tested; subsequently, CFA was used to replace these fillers at rates of (100, 20, and 10) %. MT were performed to measure the properties of the mixtures. The results indicated that replacing 20 % of the filler with CFA at 6% filler content achieved the highest MS. It was concluded that CFA can be a sustainable and viable alternative filler in AC, with optimal performance observed at the 20 % replacement level. Implication of additives can enhance the quality of the asphalt cement binder (ACB) and extend its useful life.

Sarsam, 2025, [4] investigated the possibility of modification of two types of ACB with HL and CFA additives. The treated ACB were tested for their physical properties. It was observed that the penetration value declined after implication of such additives. The softening point of the modified binders increased after implementation of the additives. Higher stiffness modulus was observed after treatment with CFA among the HL-treated or control binders. The CF also increased. Radwan et al., 2024, [5] evaluated CFA performance as a filler in AC mixtures. Four percentages of CFA were implemented as filler by aggregate weight. The dynamic creep, RM, and wheel tracking tests were used for investigating the performance characteristics of AC mixtures. It was concluded that increasing the CFA content in AC mixtures improved fatigue and rutting performance when compared with conventional AC mixture, and it can be used as an alternative filler in hot mix AC. Purnomo et al., 2024, [6] investigated the use of CFA as a filler in AC and assessed the impact of CFA as a filler on the performance of AC road materials. The study employs the MT method. It was observed that the addition of CFA as a filler to AC mixture increases the MS, durability, and stability of the mixture by reducing air voids, increasing density, and binding the AC mixture. However, it was concluded that excessive use of CFA can reduce the flexibility of the pavement and make the mixture too stiff. Alexandre et al., 2024, [7] evaluated the potential of magnetic particles from CFA as a low-cost raw material for modifying ACB. Such particles were incorporated into the ACB at (8, 6, 4 and 2) % content by weight. The materials

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were characterized by rheological, chemical, and empirical tests. X-ray Fluorescence data found that CFA contains iron, silicon, and aluminum as the main elements. The rheological test results indicated that the incorporating such particles provided better performance to the ACB in terms of both FL and PD. It was observed that the modified ACB was less susceptible to PD when compared with the neat ACB at high temperature of 64 °C. It was concluded that such easy, sustainable, and economical approach can contribute to producing more efficient AC which can resist changes in temperature.

Kmetz et al., 2024, [8] evaluated six AC mixtures modified with popular rubber additives using the wet and dry mixing processes. It was reported that wet process modification has increased resistance to fatigue failure (FF) and reduced the initial flexural stiffness (FS). The dry-process modified mixture has reduced the resistance to FF while increasing the initial FS. Sarsam, 2024, [9] investigated the influence of additives on FF mode of AC and captured the variations in the stages of FF. It was observed that implication of CFA in the AC mixture can slightly extend its FL while implication of SF improves its resistance to deterioration and extends the FL. Sarsam, 2023, [10] assessed the influence of CFA (class F) on the durability of AC through long-term ageing. The fluctuations in the initial stiffness during the loading period were monitored. It was revealed that the FL of the CFA modified AC is higher than that of the control AC mixture. It was recommended that CFA enhance the FS properties of AC when practicing ageing. Naveed et al., 2022, [11] studied the performance of AC after implementation of waste materials as additives through comparison of the stiffness modulus (SM) with the aid of creep test. The testing results showed that the excessive use of additives reduced the SM by 15%. It was concluded that the incorporation of waste material additives into the conventional AC mixtures increased the load-bearing capacity in terms of SM. Sarsam and Mashaan, 2022, [12] reported the influence of using CFA and SF additives for modification of the ACB on the characteristics of AC mixture throughout its FL. It was revealed that the use of CFA can decline the susceptibility of the mixture to ageing process, while the addition of SF can exhibit lower susceptibility to the damage by moisture when compared with other AC mixtures.

Sudarsanan and Kim, 2022, [13] discussed various FL test methods for characterizing AC mixtures, and the most common mechanistic models for predicting the FL of AC pavements based on different FL test results. The commonly used numerical models were tested for their prediction ability for the FL of AC pavement structure. The lack of reliability of some predictive models and the sensitivity of experimental results was assessed. It was concluded that such critical review of the FL predictions of AC mixtures and pavements can assess how to refine the right course of action for future research. Cheraghian et al., 2021, [14] investigated ACB modification by means of fumed silica nanoparticles. The effects of long and short-term ageing on the thermal, rheological, and microstructural ACB properties were assessed. It was concluded that such investigation paves the way for optimizing warm mix AC by nanoparticles to present enhanced green AC technology. Zheng et al., 2020, [15] studied the modification mechanism of SF modified ACB with the aid of scanning electron microscopes. It was observed that the increase in SF content up to 6 % improves the high temperature performance significantly while the FL properties of the asphalt are improved. Sawan et al., 2018, [16] investigated the impact of using different percentages of SF additive from (2 to 8) % by ACB weight on the behavior of AC mixes. The wheel tracking test was used to investigate the rutting resistance properties of the modified AC mixes. It was concluded that adding SF reduces RD by about 35.82%. Sarsam and Al-Lamy, 2015, [17] presented a comparative evaluation of AC pavement FL between conventional and modified AC under the influence of variations from the optimum of the percentage of ACB content, implementation of additives, and changing the testing temperature. It was concluded that additives were effective in enhancing the SM of AC mixture at various testing environments. Tapkin, 2014, [18] estimated the FL of AC mixtures using artificial neural networks. Different types of CFA were implemented as filler replacing agents in a dense AC mixture. FL tests were performed using DITS apparatus under controlled stress conditions. For determination of FL, the initiation of macro crack was accepted as the main criteria to terminate the test. The experimental data were implemented as training set. It was reported that very reasonable estimates of FL of AC mixtures were obtained. It was concluded that such approach provides time saving, real economy, and allows detecting the influence of CFA replacement and composition on the FL and other mechanical properties of AC mixtures.

The aim of the present work is to compare the influence of modification of AC with additives (SF and CFA) on (PD - FL) relationship. Preliminary prediction of FL and PD within the investigated material ranges and the testing conditions after modification of AC with additives are conducted. AC Beam specimens are prepared with control and CFA and SF modifying additives. Specimens are tested for DFF using FPBB apparatus under three CSL of (250, 400, and 750) Microstrain and 20 °C environment. The PD-FL plots are modeled, results are analyzed, and conclusions were addressed. The obtained Mathematical models may be implemented for fast and preliminary prediction of the influence of additives on PD-FL of AC within the investigated material ranges and instant detection of AC quality.

2. Materials and Methods

2.1. Asphalt Cement Binder (ACB)

The ACB of (40-50) penetration grade and a softening point of 49°C was used in the present study. It is obtained from AL-Nasiria oil Refinery; Figure 1 presents the physical properties of ACB before and after practicing ageing by thin film oven test. The testing was conducted according to ASTM, 2015, [19] procedures.

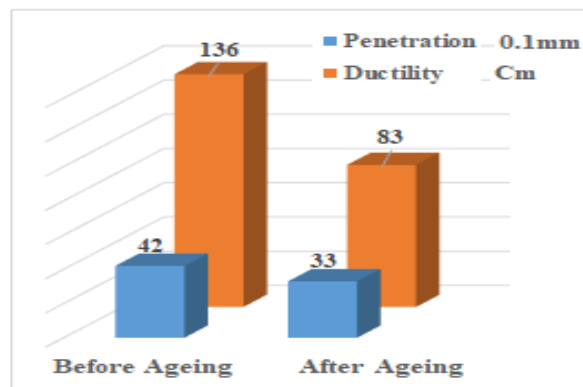


Figure 1. Physical properties of ACB

2.2. Coarse and fine aggregates

Crushed coarse aggregate was obtained from AL-Ukhaider- Karbala quarry. Crushed sand and natural sand combination are used as Fine aggregate according to SCRB specification, 2003, [20]. The physical properties of aggregates are demonstrated in Figure 2.

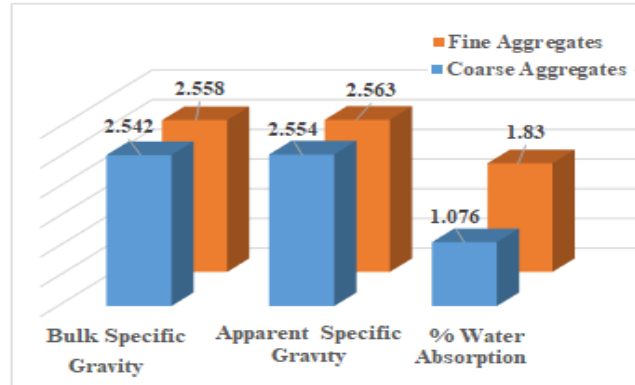


Figure 2. The physical properties of aggregates

2.3. Mineral filler

Limestone dust was obtained from lime factory at Karbala and implemented as mineral filler. The bulk specific gravity of the filler is 2.617, and 94 % of the filler is finer than 75 microns.

2.4. Additives

Two types of Additives were used in different percentages as partial substitutes of filler or ACB. CFA is obtained as waste material from local markets and used as partial substitute of mineral fillers. SF fluffy powder is obtained from local market and used as partial substitute of ACB. Table 1 presents the physical properties and chemical composition of additives. The testing was conducted according to ASTM, 2015, [19] procedures.

Table 1. Physical properties and chemical compositions of additives

Property	Silica Fumes (SF)	Coal Fly Ash (CFA)
Percent finer than 75 microns	100	98
Specific gravity	2.134	2.010
Specific surface area (m ² / kg)	200000	650
% SiO ₂	99.1	61.9
% Al ₂ O ₃	< 0.035	28.8
% CaO	0.03	0.88
% Na ₂ O	< 0.07	0.26
Loss on ignition	0.73	0.86
MgO	52 PPM	0.34 %
Fe ₂ O ₃	35 PPM	2.6 %



Figure 3. The implemented Additives

2.5. Combined gradation

Selection of aggregate gradations was based on SCRB, 2003, [20] specification which is suitable for wearing course AC pavement layer, with 12.5 (mm) nominal maximum size of aggregates. Figure 4 shows the selected aggregate gradations.

2.6. Modification of AC mixture with additives

Modification of AC was conducted with the aid of two different processes, the first process is the wet process, ACB was heated and maintained to a 150 °C, and SF modifier was added gradually and blended. Two percentages (1, and 2) % by weight of ACB were tried. The blending was conducted for 20 minutes at a blending speed of 1300 RPM to promote the possible chemical and physical bonding of the binder-additive components. Such blending process was made according to the mentioned process by Sarsam, 2025, [4]; and Sarsam and Al-Lamy, 2015, [17]. During the blending process, the ACB swells as an indication of possible reaction with SF. The second process is the dry process when the CFA was added to the aggregates as partial substitute of mineral filler. Two percentages of CFA were implemented, (2, and 4) %.

The prepared control and treated asphalt-aggregate mixtures were subjected to short term oven aging process for 4 hours at 135 °C temperature according to AASHTO PP2, 1999, [21]. The short-term aged AC mixture was cast in preheated slab mold (400 mm by 300 mm by 60 mm) size. Samples were prepared at OAC of 4.9%. More details of obtaining the OAC can be found in Sarsam and Al-Lamy, 2015, [17]. The mixtures were subjected to roller compaction as per EN12697-33, 2007, [22] to achieve the target density for the OAC. The applied static load was 5 kN and the compaction temperature was maintained. More details of the preparation process could be found at Sarsam and Al-Lamy, 2015, [17].

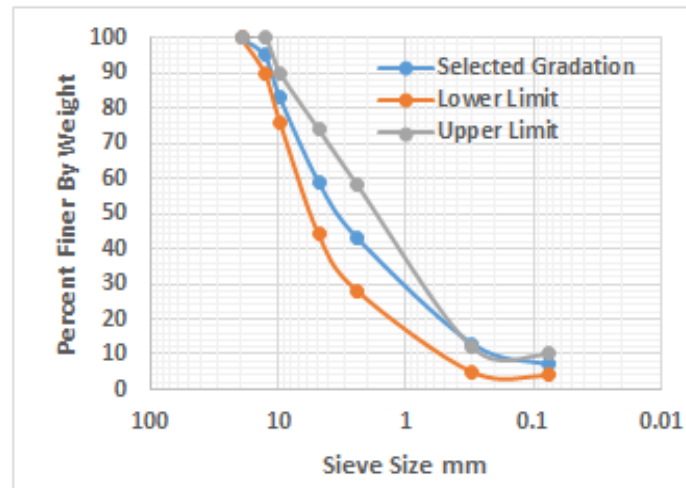


Figure 4. Combined aggregates gradation of wearing course as per SCRB, 2003, [20]

The compacted slabs were left to cool overnight and then beam specimens of 400mm x 50mm x60 mm were obtained from the AC slab samples using Diamond-cutter according to ASTM, 2015, [19]. The total number of AC beam specimens was 45 while the total number of the prepared AC slab samples was seven. Figure 5 exhibits the short-term ageing and roller compaction device. Specimens were tested in triplicate, and their average value was considered for further analysis. Such limited sample size may be used to preliminary prediction of FL and PD within the investigated material ranges and the testing conditions. The maximum accepted tolerance value of the test results was 5 % between the triplicate specimens. Table 2 demonstrates the Marshall properties of the prepared AC mixture.

Table 2. Marshall properties of the prepared mixtures

AC mixture type	Binder content (%)	Bulk density (gm/cm ³)	Marshall stability (kN)	Marshall flow (mm)	VMA (%)	Vfb (%)	Vv (%)
Control	4.9	2.273	11.3	2.9	15.1	72.5	4.2
Silica fumes treated	4.9	2.275	10.8	3.1	15.0	74.1	4.0
Coal fly ash treated	4.9	2.268	9.7	3.4	14.8	69.0	4.3

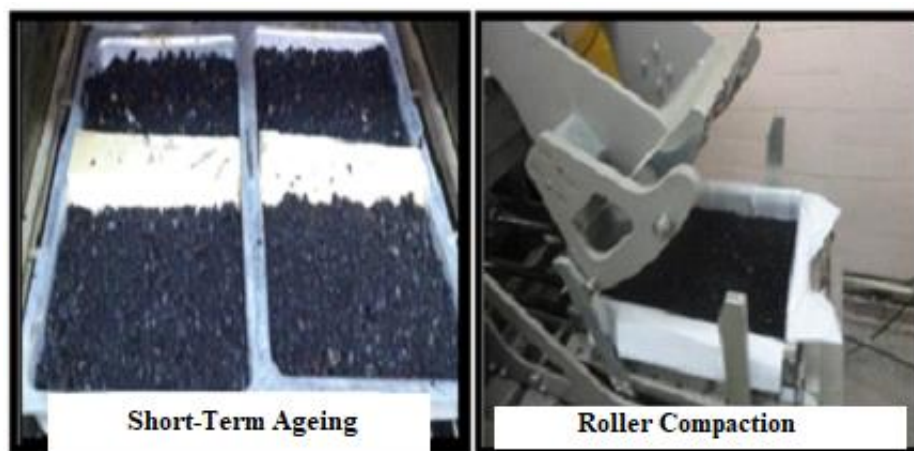


Figure 5. Short-term ageing and roller compaction devices

2.7. Dynamic Flexural Fatigue (DFF) Beam Testing

The FL of AC beam specimens were measured at CSL of (750, 400, and 250) microstrain. The DFF was conducted using FPBB Test as per AASHTO T 321, 2010,[23]. specimens were tested at 20 °C environment. Figure 6 exhibits the DFF beam testing apparatus. The FFT is performed by placing the AC beam in Dynamic four points bending beam testing chamber at the specified strain level. During the test, the AC beam is held in place by four clamps and a dynamic haversine (sinusoidal) load is applied to the two inner clamps with the outer clamps providing a reaction load. This setup produces a constant bending moment over the center portion of the beam (between the two inside clamps). The deflection caused by the loading is measured at the center of the beam after each loading cycle by LVDT. The number of loading cycles to failure can then give an estimate of a particular AC mixture's FL. Figure 7 demonstrates the schematic diagram of the test setup. The loading was applied through 0.1 second followed by 0.9 second of rest periods. Damage accumulation in the beam specimens was monitored through the changes of PD and stiffness. The fatigue failure criteria were considered where the stiffness of the beams declines to 50% of their initial stiffness due to dynamic loading.

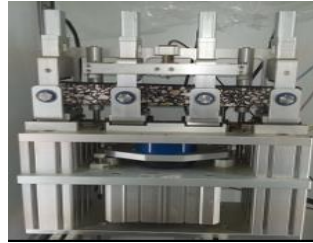


Figure 6. DFF beam testing apparatus

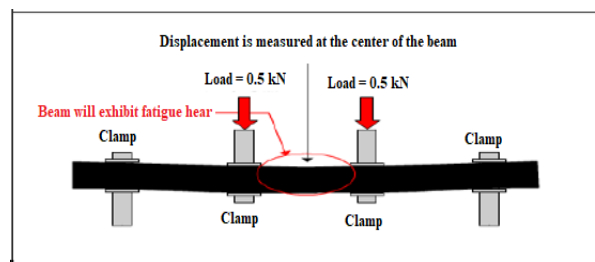


Figure 7. Schematic diagram of the FPBB test setup

3. Results and Discussions

3.1. Influence of CSL and additives on FL

As demonstrated in Figure 8, FL declined as the CSL increases regardless of the implemented additives. However, the FL increased after additives treatment. At low CSL of 250 microstrain, FL was extended by (17.6, 46) % and (38.4, 94.5) % after treatment with (1, and 2) % SF and (2, and 4) % CFA respectively as compared with those of the control AC mixture. Such behavior may be attributed to possible chemical and physical reactions that occurred and changed the properties of the ACB. Radwan et al., 2026, [1]; and Sarsam, 2025, [4] reported similar behavior. When the CSL was moderate (400 microstrain), FL was extended by (20.5, 115) % and (113.5, 221) % after treatment with (1, and 2) % SF and (2, and 4) % CFA respectively as compared with those of the control AC mixture. When the CSL was high (750 microstrain), FL was extended by (7.8, 58.7) % and (40.7, 73.7) % after treatment with (1, and 2) % SF and (2, and 4) % CFA respectively as compared with those of the control AC mixture. It can be detected that implementation of 4 % of CFA into the AC mixture had extended its FL. Such behavior agrees with the work reported by Sawan et al., 2018.,[16]. On the other hand, the rate of decline in the FL of AC was (83.2, and 96.5) % for control AC mixture when the CSL rises from (250 to 400 and 750) microstrain respectively. When the AC mixture was digested with additives, the rate of decline in the FL of AC was (75.2, and 96.2) % for 2 % SF treated mixture and (72.3, and 96.9) % for 4 % CFA treated mixture when the CSL rises from (250 to 400 and 750) microstrain respectively. Similar findings were reported by Ergeshov et al., 2026,[2].

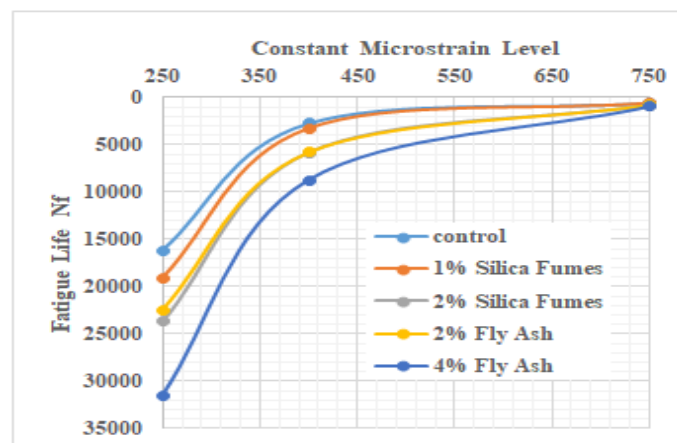


Figure 8. Influence of CSL and additives on FL

3.2. Influence of PD on FL

Figure 9 exhibits the influence of PD on the FL of AC under various CSL. It can be noticed that as PD increases, the FL declines, indicating distressed pavement. However, as the CSL rises, the PD also increases. The relationship between FL and PD for control and additives treated AC mixtures is a power mathematical model with high coefficient of determination. The trend of the relationship declines sharply at high CSL when changing from (750 to 400) microstrain. However, the rate of decline of the relationship is gentle when the CSL changes from (400 to 250) microstrain regardless of the implemented additives. Such behavior may indicate sensitivity of the relationship to the changes in the applied CSL. The implementation of 4 % CFA exhibits the highest increment in FL when compared with control or with mixture treated with 2 % SF at the PD level regardless of the applied CSL. Mixtures with 4 % CFA and 2 % of SF were selected for further investigations based on their influence on FL.

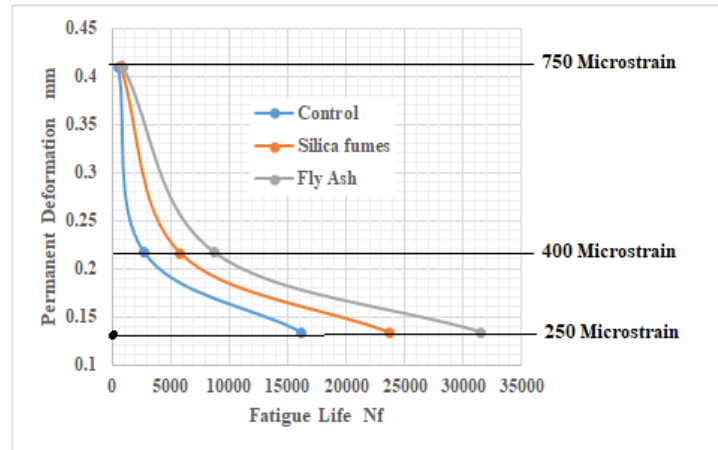


Figure 9. Influence of PD on FL

After 10000 repetitions of DFS, the PD of the mixtures was (0.16, 0.19, and 0.21) mm for control, SF treated, and CFA treated AC mixtures respectively. Such behavior may be attributed to the fact that additives create more flexibility in the structure of AC which can sustain more deformation and extend the FL of AC when compared with the behavior of the control AC mixture. At 10000 load repetitions, treated AC mixture with CFA and SF additives exhibits higher PD (23.5, and 11.7) % than that of the control AC mixture respectively. However, higher FL is exhibited by the additives treated AC mixtures regardless of the CSL as compared with the control AC mixture. Similar behavior was reported by Radwan et al., 2026,[1]. When the CSL rises from (250 to 400) microstrain, the PD increases by (62.2, 61.7, and 62.1) % for (control, SF treated, and CFA treated) mixtures respectively, while it increases by (206, 206.6, and 205.8) % for (control, SF treated, and CFA treated) mixtures respectively when the CSL rises from (250 to 750) microstrain. It can be noticed that under low and medium CSL, implementation of additives exhibits an influence on FL, while under high CSL, the variation in FL among implementation of additives is well detected. Similar findings were reported by Kmetz et al., 2024,[8]; Naveed et al., 2022,[11]. Table 3 demonstrates the obtained mathematical power models of the (FL-PD) relationship. The scale coefficient represents PD after starting the DFS while the exponent is the rate of change in deformation through the FL under the applied DFS. The analysis of data provided power mathematical regression models which correlate the PD of AC mixtures with the FL cycle for control and modified AC mixtures. Such obtained mathematical power regression models with high coefficients of determination (R^2) and reasonable standard error of estimate (SEE) may be implemented for fast and preliminary prediction of the expected influence of additives within the investigated material ranges and testing conditions. Due to the limited number of tested specimens, high R^2 exhibits empirical nature and limited domain.

Table 3. Mathematical models

Mixture type	Scale coefficient	Exponent	Mathematical Power model	R^2	SEE
Control AC	3.2196	- 0.332	$Y=3.219 X^{(-0.332)}$	0.9893	0.08
Silica Fumes (SF) treated	3.6969	- 0.329	$Y=3.6969 X^{(-0.329)}$	0.9997	0.06
Coal Fly Ash (CFA) treated	3.7030	- 0.318	$Y=3.7030 X^{(-0.318)}$	0.9968	0.07
Y= PD X=FL (number of flexural stress repetitions)					

4. Conclusions

Limitation of the obtained models are based on the conducted testing and implemented materials. At low CSL of 250 microstrain, FL was extended by (17.6, 46) % and (38.4, 94.5) % after treatment with (1, and 2) % SF and (2, and 4) % CFA respectively as compared with those of the control AC mixture. When the CSL was moderate (400 microstrain), FL was extended by (20.5, 115) % and (113.5, 221) % after treatment with (1, and 2) % SF and (2, and 4) % CFA respectively as compared with those of the control AC mixture. When the CSL was high (750 microstrain), FL was extended by (7.8, 58.7) % and (40.7, 73.7) % after treatment with (1, and 2) % SF and (2, and 4) % CFA respectively as compared with those of the control AC mixture. After 10000 repetitions of DFS, the PD of the mixtures was (0.16, 0.19, and 0.21) mm for control, SF treated, and CFA treated AC mixtures respectively. The implementation of 4 % CFA exhibits high increment in FL when compared with control or with mixture treated with 2 % SF at the PD level regardless of the applied CSL. The obtained mathematical power regression models with high coefficients of determination exhibit empirical nature and limited domain and may be implemented for fast and initially predict the change in FL due to PD after modification of AC with additives within the investigated material ranges and the testing conditions after modification of AC with additives and instant detection of AC quality.

Author Contributions

S.I.S.: Introduction, Methodology, Formal Analysis, Investigation, Writing – Original Draft, Writing – Review & Editing.

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Data Availability Statement

The data presented in this study are available from the corresponding author upon reasonable request.

Conflict of Interest Statement

The author declares that he has no conflict of interest. He has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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