Performance Evaluation of Cement Grouts Using Industrial By-Products for Semi-Flexible Pavements

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Abstract

Semi-flexible pavement (SFP), a hybrid pavement system that combines open-graded asphalt with cementitious grout, offers enhanced durability, load-bearing capacity, and resistance to rutting compared to conventional pavement systems. However, the environmental impact of cement usage in grout formulations remains a significant concern due to its high carbon footprint. This study explores the feasibility of partially replacing ordinary Portland cement with industrial by-products, fly ash (FA) and silica fume (SF), in cement grouts for SFP applications. Grout mixtures with 5% and 10% replacements of FA and SF were prepared and evaluated for flowability, compressive strength (at 1, 7, and 28 days), and flexural strength (at 28 days). The study found that fly ash (FA) improves grout flow and long-term compressive strength, with 10% FA achieving a 16% increase at 28 days. Silica fume (SF) enhances both early and overall strength but reduces flowability at higher doses. Both additives improved flexural strength, with 5% FA showing a 28% increase over the target. Based on optimal flow (11–16 seconds) and compressive strength (60 MPa), the best performance was observed with 10% FA and 5% SF. These results suggest that FA and SF can serve as effective and sustainable partial replacements for cement, maintaining or enhancing mechanical performance while lowering environmental impact. This makes them suitable for use in semi-flexible pavement (SFP) applications, contributing to both durability and sustainability goals.

Keywords: semi-flexible pavement; cement grouts; fly ash; silica fume

1. Introduction

Semi-flexible pavement (SFP), also known as Grouted Macadam, has gained growing attention due to its unique structure. It consists of an open-graded asphalt mix infused with specially formulated cementitious grouts [1]. During construction, the grout infiltrates the interconnected voids within the asphalt, bonding with the mastic—composed of fine aggregates, filler, and binder. This integration forms a strong, composite structure capable of handling high loads, resisting rutting, and maintaining shape under traffic stress [2]. Offering a balance between strength and flexibility, SFP has proven to be a promising alternative to conventional pavement types [3-5].

A key feature of SFP is the grout's ability to occupy around 25–35% of the air voids in the porous asphalt layer [5-7]. This enhances its mechanical performance, especially when compared to traditional rigid and flexible pavements. Its durability and high rutting resistance make it suitable for demanding applications [8]. Research by Koting et al. further demonstrated its resilience against fatigue, oil spills, and permanent deformation [9].

The performance of Semi-Flexible Pavement (SFP) depends mainly on the type and quality of cementitious grout used to fill the interconnected voids in its porous asphalt base. Ordinary

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Portland Cement has long served as the standard binder in these grouts due to its consistent strength and widespread availability. However, growing attention to the environmental and economic drawbacks of OPC, particularly its energy-intensive production and significant carbon footprint, has led researchers to investigate more sustainable alternatives. Materials such as fly ash, ground granulated blast furnace slag, silica fume, and agricultural residues like bagasse ash have shown promise as partial or full replacements. These alternatives not only offer cost savings but also contribute to more sustainable construction practices by recycling industrial and agricultural waste. Their use helps cut down on cement consumption and reduces greenhouse gas emissions, aligning with broader efforts to create more environmentally responsible infrastructure [4, 10].

However, the environmental footprint of concrete construction remains a concern, primarily due to cement's high energy demand and its role in global CO_2 emissions [11]. To reduce these impacts, researchers have explored partial replacement of cement with supplementary cementitious materials (SCMs), which offer ecological and performance benefits. SCMs like fly ash, bentonite, coconut ash, sugarcane bagasse ash, and silica fume etc have shown potential in improving durability, enhancing resistance to aggressive environments, and lowering permeability in concrete systems [11-14]. Using waste materials or mineral admixtures as substitutes for cement not only supports sustainability but also improves performance and reduces costs [15].

Despite these advancements, Portland cement remains a core component in grout for SFP, contributing to environmental challenges. As a solution, studies are increasingly focusing on incorporating industrial by-products into grout formulations. Yet, limited research exists on using fly ash and silica fume specifically in cement grouts for SFP. Addressing this gap, the current study evaluates the partial replacement of cement with fly ash (FA) and silica fume (SF)—both by-products of industrial processes. The prepared grouts were tested for flow characteristics, compressive strength (after 1, 7, and 28 days), and flexural strength. The study aims to lower material costs and environmental impact without compromising the mechanical performance of SFP systems.

2. Materials and Methods

The In this study, fly ash and silica fume were used as a partial replacement of ordinary Portland cement for the preparation of cement grouts for grouted macadam pavements. w/c ratio of 0.35 and dose of superplasticizer of 1% were kept constant for all grouts and were determined by author's previous research. Cement was replaced with 5 and 10 % fly ash and silica fume. The grouts were mixed and prepared according to ASTM C305 [16].

After preparing cement grouts, flow test on fresh grout were performed using flow cone apparatus in accordance with ASTM C-939. According to literature, the flow out time of grout from the flow cone shall be in the range of 11 to 16 sec. In this test, 1750 mL of fresh grout was poured into the flow cone with closed valve at bottom. Soon after poring, the valve was opened and time taken to empty the flow cone was recorded by stopwatch.

In addition to flow test, the cubes of size 50 mm were filled from cement grouts and kept for 24 hours and were then demolded. After that the cubes were placed in water for curing until test date. After curing the cubes were subjected to compressive test to determine the compressive strength at 1d, 7d and 28 days curing ages. Beam specimens of size (need to write the size) were also prepared and tested for flexural strength test at 28d curing.

3. Results and Discussion

3.1. Flow value of grouts

The flow value of cement grouts incorporating fly ash (FA) and silica fume (SF) is presented in the Figure 1, with the acceptable range defined as 11 to 16 seconds. The control grout exhibits a flow value of approximately 12.5 seconds, which remains within the acceptable range. The inclusion of 5% FA results in a flow value similar to the control, while increasing FA to 10% reduces the flow to around 11 seconds, marking a decrease of approximately 12% compared to the control.

Conversely, adding 5% SF increases the flow value to about 13 seconds (4% higher than the control), whereas 10% SF significantly increases the flow to around 16.5 seconds, exceeding the upper acceptable limit by 3%. This indicates that while FA slightly improves flowability, SF reduces it, with higher SF content leading to excessive thickening, which may impact the workability and pumpability of the grout. The flow results are comparable to other studies that utilize different supplementary cementitious materials, such as pumice stone ash, marble dust, and date palm ash [4, 17, 18].

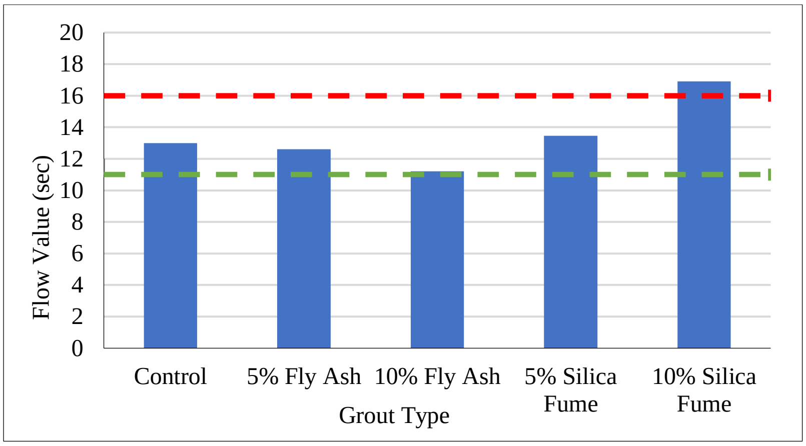

Figure 1: Flow value of cement grouts containing fly ash and silica fume

3.2. Compressive and flexural strength results

The compressive strength results of cement grouts incorporating fly ash (FA) and silica fume (SF) at 1, 7, and 28 days of curing are compared with the target strengths of 10 MPa, 35 MPa, and 60 MPa, respectively as shown in **Figure 2**. At 1 day, all grout mixtures exceed the target strength, with values ranging from approximately 25 MPa to 30 MPa, indicating early strength development. At 7 days, all mixtures meet or exceed the 35 MPa target, with the highest strength observed in the 10% FA mix (~50 MPa), showing a 43% increase over the target. At 28 days, the control and modified grouts surpass the 60 MPa target, with the highest value (~70 MPa) achieved in the 10% FA mix, which represents a 16% increase. SF-modified grouts also exhibit strength enhancement, though slightly lower than the 10% FA mix. This trend suggests that FA contributes to long-term strength gain, while SF enhances early and overall strength, making both beneficial for grout performance. The observed improvement in compressive strength with increasing fly ash and silica fume content in the present study is consistent with findings from previous research. Several studies have demonstrated that incorporating proportions of fly ash and silica fume as partial replacements for cement in mortar and concrete enhances compressive strength. This improvement is primarily attributed to the pozzolanic reactions of these supplementary cementitious materials, which contribute to the formation of additional calcium silicate hydrate (C-S-H) gel, thereby refining the microstructure and increasing overall strength [9, 19-24].

The flexural strength of cement grouts at 28 days curing is evaluated against the target strength of 7 MPa. The flexural strength results are presented in **Figure 3**. The control mix achieves a flexural strength of approximately 7 MPa, meeting the target. The inclusion of 5% FA significantly enhances flexural strength to around 9 MPa, representing a 28% increase over the target. The 10% FA mix exhibited notable improvement in flexural strength, reaching approximately 8 MPa—about 14% above the target value. Similarly, grouts with silica fume (SF) also performed well, with the 5% SF mix achieving around 7.5 MPa (a 7% increase), and the 10% SF mix reaching 8 MPa (14% increase). These outcomes suggest that both FA and SF contribute positively to tensile performance, with FA providing slightly greater enhancement. The results of this study, in line with existing literature, affirm the beneficial impact of FA and SF on the flexural strength of cement-based materials. Incorporating 5–10% FA led to 14–28% improvement, while similar dosages of SF resulted in 7–14% gains. These enhancements are primarily attributed to their pozzolanic reactivity and ability to refine the microstructure. Findings are consistent with earlier studies by Siddique (2011) and Mazloom et al. (2004), confirming their effectiveness in improving tensile behavior [25-27].

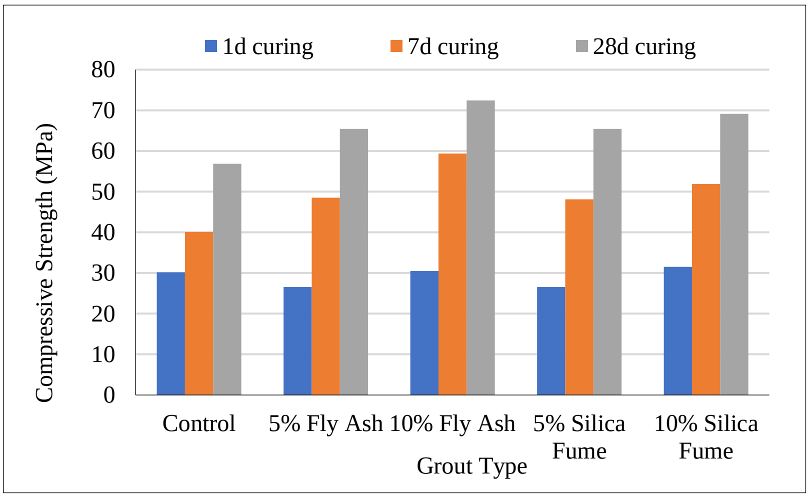

Figure 2: Compressive strength of grouts at 1d, 7d and 28d curing

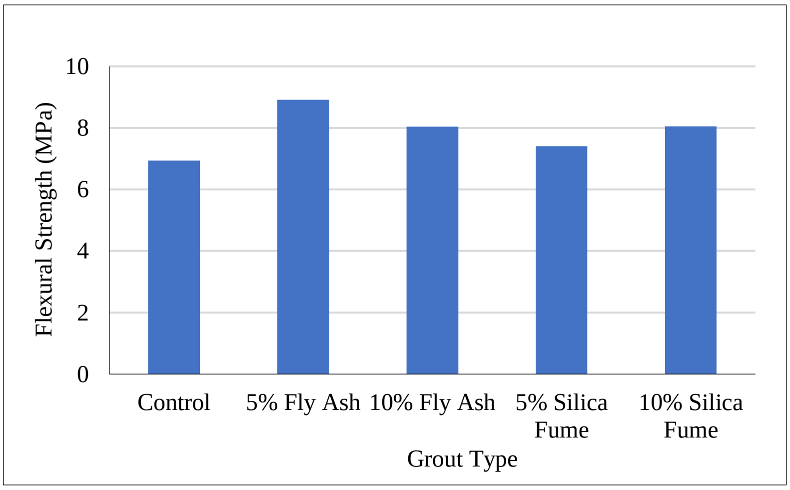

Figure 3: Flexural strength of cement grouts at 28d curing

This study has practical applications in the construction of semi-flexible pavements. Large quantities of fly ash and silica fume are generated as industrial byproducts, and due to their pozzolanic properties, they can be effectively utilized as partial replacements for cement. Furthermore, this type of pavement is specialized for areas subjected to heavy vehicular loads, making it suitable for applications such as urban metro bus routes, bus terminals, industrial parking lots, airport taxiways, and hangars

5. Conclusions

This study explored the use of fly ash (FA) and silica fume (SF) as partial replacements for ordinary Portland cement in cement grouts for semi-flexible pavement (SFP) applications. The key findings are as follows:

- Fly ash improved the flowability of grouts, with 10% FA reducing flow time by 12% compared to the control. In contrast, SF increased flow time, with 10% SF exceeding the acceptable range, indicating potential challenges in workability and pumpability at higher concentrations.
- Compressive Strength: Both FA and SF enhanced compressive strength at all curing ages. FA demonstrated superior long-term strength, with 10% FA achieving a 16% increase in 28-day compressive strength compared to the control. SF contributed to early strength development, with all SF-modified grouts exceeding target strengths at 1 and 7 days.
- Flexural Strength: FA and SF significantly improved flexural strength, with 5% FA showing the highest enhancement (28% above the target). SF also contributed positively, with 10% SF achieving a 14% increase over the target.
- Environmental and Practical Implications: The use of FA and SF as partial cement replacements offers a sustainable solution to reduce the environmental impact of cement production while maintaining or enhancing grout performance. FA, in particular, stands out for its ability to improve both flowability and mechanical properties, making it a promising alternative for SFP applications.
- This study demonstrates the viability of incorporating industrial by-products like FA and SF into cement grouts for SFP, providing a pathway toward more sustainable and high-performance pavement systems. Future research should focus on optimizing replacement ratios and exploring additional by-products to further enhance environmental and mechanical benefits.

Data Availability Statement: All data used in this study in included in this article.

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SFP	Semi-flexible pavement
FA	Fly ash
SF	Silica fume
SCM	supplementary cementing materials
ASTM	American Association of Testing Materials

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