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Influence of Particle Size of Fillers on the Development of Foundry Sand-Polyurethane Composite Mixture: A Laboratory Investigation

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ABSTRACT: The escalating global challenges of resource depletion and environmental degradation have urged the shift towards the utilization of industrial by-products, thus transforming them into functional and valuable secondary resources, thereby reevaluating traditional industrial practices. Over recent years, polyurethane has gained popularity as a quick-setting binder for repairing and reinforcing civil engineering infrastructure projects. This study focuses on understanding the influence of particle size of the filler materials in the Foundry sand-polyurethane composite construction material. Two industrial by-products, namely silica fumes and fly ash, have been used as filler material to understand the influence on the mechanical properties of the composite mixture. The mixture is prepared by adding 6% polyurethane, and the silica fumes and fly ash are introduced to the mix by partially replacing the foundry sand from 0% to 50% by weight. The mechanical properties (strength) and the microstructural analysis are done to understand the influence of these finer fractions. Introducing fly ash into the foundry sand gave a consistent result in the unconfined strength of the mixture. The strength gradually increased with the addition of the fly ash, which can be attributed to the increased packing arrangement and the formation of a denser structure as the fly ash filled the voids of the foundry sand. Although with the introduction of the silica fumes, the strength increased at 10% replacement, it reduced to half and more with the higher replacement ratios due to the loosening effect. Microstructural studies revealed non-uniform mixing with the formation of silica fume lumps when mixed with foundry sand, causing zones of weaker sections. Therefore, a higher polyurethane content is required for improved strength and homogeneous mixing when the fillers' particle sizes are smaller.

KEYWORDS: Foundry sand, Polyurethane, Filler material, Strength, Waste Valorization

1 INTRODUCTION

Polyurethane (PU), often called a green polymer, plays a remarkable role in various civil engineering applications, particularly ground improvement, foundation remediation techniques, and pavement engineering. The excellent engineering properties, corrosion resistance, high energy absorption, thermal and chemical resistance, and ease of use have contributed to the popularity of PU (Ashida, 2006; Sharmin and Zafar, 2012). The applications of the PU range from adhesives, coatings, sealants, waterproofing, insulations, etc (Chattopadhyay and Raju, 2007; Gadea et al., 2010, 2010; Hradil et al., 2014; Mishra and Kumar Sinha, 2010). The transportation, construction and building sectors involving pavement projects consume 20.3% and 35.9% of the total amount of PU materials utilised, respectively (Li et al., 2021). The excellent bond strength and fast curing time of the PU render it an optimal grouting material for the stabilization and re-leveling of settled foundations (Dirgėlienė and Kordušas, 2024). Recently, the PU has been widely used in pavement engineering for the development of cold mixes to substitute the dependency on conventional energy-intensive asphalt mixture for road surfacing and repair works (Liu et al., 2019; Min et al., 2019; Wu et al., 2023; Yang et al., 2021).

The PU has been used to valorise the industrial by-products from fly ash to sand and waste materials from construction sites. PU has been utilized to strengthen reclaimed calcareous sand, a material characterized by low particle strength and susceptibility to crushing, transforming it into a load-bearing material suitable for construction applications (Chang and Deng, 2025; Wu et al., 2025). This demonstrates a viable pathway for valorizing Construction and Demolition Waste (CDW), transforming it from a waste product into a valuable material for meaningful applications like reef constructions, embankment construction, etc. Although using CDW and industrial by-products with PU has drawn much attention, there is a significant lack of information in the literature about how the filler materials affect the composite's properties. Fewer studies have attempted to comprehend the role of filler particle size distribution or how it affects the performance of the final composite. This research addresses this deficiency by analysing how the physical attributes of fillers, particularly particle size, impact the microstructural and mechanical properties of the developed composite samples.

2 MATERIALS

The primary raw material used in the study was Waste Foundry Sand (WFS). Foundry sand, labelled as a waste product, is an industrial by-product of the metal casting or foundry moulding industry. WFS was supplied for the study from Belgaum, Karnataka, India. Two industrial by-products- Fly ash (FA) and silica fumes (SF) were used as the filler materials in the study. The fly ash used was Class F, supplied from the coal-powered thermal power plant in Farraka, West Bengal. The commercially available silica fumes, supplied locally and made by Sika India Pvt. Ltd., were used as the second filler material. The physical properties of the raw materials used in the study are shown in Table 1. Polyurethane (PU), often called the green polymer, was used as the binder. The two-component polyurethane used in the study had two parts: parts A (polymers of glycerol, propylene oxide, and polypropylene glycols) and B (diphenylmethane diisocyanate), which were mixed in equal volumetric proportions to make the PU binder. The PU was supplied by Fosroc Chemicals (India) Pvt. Ltd.

3 METHODS

The present study focused on casting and testing the unconfined compression strength (UCS) samples of diameter 38mm and height 76mm. The PU content considered for the study was 6%, and was chosen based on the literature of previous research using similar materials (Yang et al., 2021). The PU was made by mixing equal volumes of parts A and B using a mechanical stirrer. The WFS was used as the primary material for casting the samples. The UCS samples were cast by taking the dry weight of the WFS corresponding to the maximum dry density and mixing the WFS with the PU. The extruded UCS samples were kept for 24 hours for open-air curing at ambient temperature before testing. Figure 1 shows the schematic diagram of the mixing method adopted. To understand the effect of the filler materials (FA and SF) on the unconfined compressive strength of the PU-WFS mixture, the foundry sand was replaced by the filler materials at a rate of 10% to 50% by weight of WFS in increments of 10%. The UCS samples were cast and tested to determine the effect of FA and SF as filler materials on the strength of PU-WFS composites.

Moreover, the casted samples were submerged in water for 28 days and tested to evaluate the strength reduction of the samples under water submergence.

Table 1. Physical properties of the materials used in the study.

Property	Values		
	Foundry Sand	Fly Ash	Silica Fumes
Specific Gravity	2.65	1.93	2.18
Maximum Dry Density (g/cc)*	1.68	1.445	0.755
OMC*	9%	18%	22%
LOI	5.03%	0.59%	4.52%
pH	8.17	7.8	8.95
Particle size distribution (%)			
Fine sand (0.425- 0.075mm)	89.4	87.03	70
Silt (0.075-0.002mm)	8.98	10.82	30
Clay (<0.002mm)	1.62	1.02	0

**Results of Standard Proctor test (ASTM D698)*

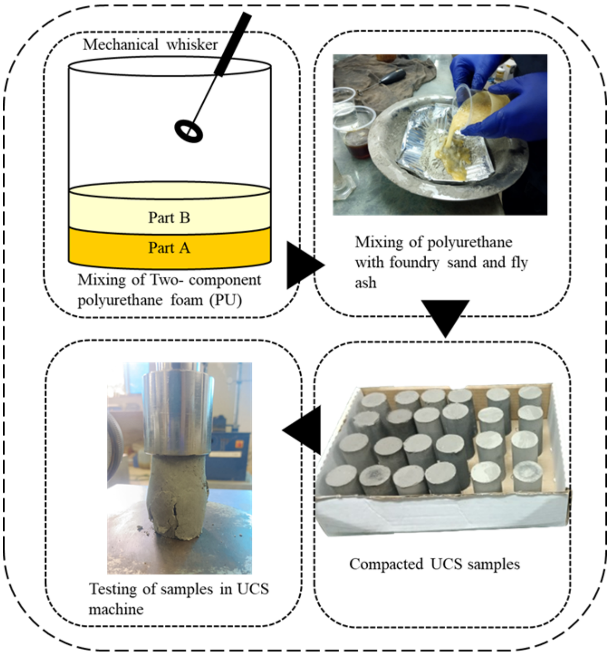

Figure 1. Figure showing the mixing and casting methodology adopted.

4 RESULTS AND DISCUSSIONS

4.1 *Influence of filler percentage on UCS*

The influence of the filler materials on the strength of the PU-WFS composite was evaluated by incorporating portions of fly ash and silica fumes in the mixture and testing the mixture after 24 hours of ambient temperature curing. Figure 2 shows the unconfined compressive strength (UCS) results of the samples when a certain percentage by weight of the waste foundry sand has been replaced by the filler materials (FA and SF). The strength of the PU_WFS-FA composites increased with the partial replacement of the foundry sand with the fly ash. The UCS increased from 11 MPa to 12.4 MPa when 10% of fly ash was incorporated with the WFS mixture. When FA replaced 50% of WFS, the strength increased by 50%, from 11 MPa to 16.5 MPa. Serving as a micro-filler, the fly ash (FA) occupied the voids within the coarse-grained foundry sand (WFS) skeleton, which optimized the particle packing of the composite. This process reduced the void ratio and resulted in a corresponding increase in the bulk density and inter-particle friction. Figure 3 shows the FESEM image analysis of the WFS-FA samples coated with PU. It was clear from the FESEM analysis that a denser structure was formed with fly ash positioned in the inter-particle spaces of the PU-WFS skeleton, thus reducing the void spaces between the coarser WFS particles. A more continous and compact matrix structure could be visible with fewer void spaces with the increase in the FA percentages.

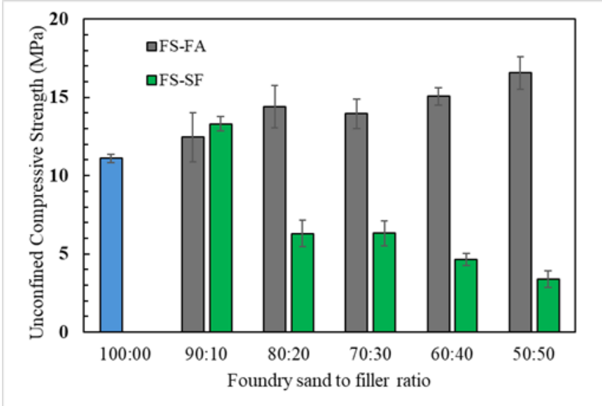

Figure 2. Unconfined Compressive Strength results of the PU_WFS-FA and PU_WFS-SF samples.

The binding of the material was the result of the polymerization process of the polyurethane due to the reaction happening between the isocyanate (-NCO) and the polyol containing multiple hydroxyl groups (-OH). The foundry sand, fly ash, and silica fumes are a natural mixture of aluminosilicates (SiO_2 and Al_2O_3). The surface of these particles naturally contains a significant number of -OH groups, which react with the -NCO groups of the PU during the curing process. This reaction develops covalent bonds at the interface, creating strong chemical bonds between the organic polymer and the inorganic filler materials. This was evident from the FTIR analysis results (Figure 4), which showed a strong absorption peak around 1080 cm^{-1}, indicating the stretching vibrations of the Si-O-Si network. In addition, the broadening of peaks in the 1080–810 cm^{-1} region corresponds to Si–O–Si and Al–O–Si stretching vibrations, indicating that the siliceous and aluminosilicate components of WFS are actively involved in the formation of the polyurethane (PU) network and interfacial cross-linking.The intensity of these peaks became more pronounced with the increase in the FA and SF percentages. The observed increase in the intensity of the absorption band does not represent the production of new chemical bonds at the interface; rather, it represents a proportional increase in the concentration of the pre-existing covalent Si–O–Si links as the mass fraction of filler is increased.

The stretching vibration of the –NCO group, which contributes to chemical adhesion with the foundry sand (WFS), is evidenced by a weak band near 2270 cm^{-1}(Wu et al., 2023). This band reflects the reaction of isocyanate groups with surface functionalities on WFS, promoting covalent bonding and interfacial anchorage. In addition, mechanical interlocking, when the spherical FA flows into and gets encapsulated with the liquid PU, was also responsible for the matrix formation. Simultaneously, the elastic property and the tensile capacity of the PU provided a continous and deformable bridge between the WFS particles, enabling sufficient stress transfer. A rigid network was developed when the PU cured and solidified (Wu et al., 2025).

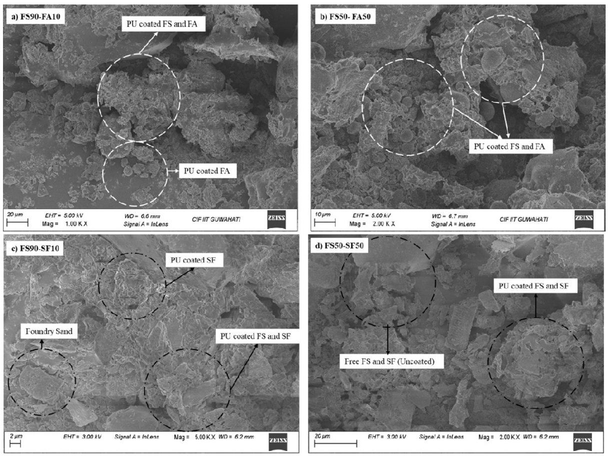

Figure 3. FESEM image analysis of the a) FS90-FA10, b) FS50-FA50, c) FS90-SF10, and d) FS50-SF50 samples.

However, the introduction of more FA into the composite mixture led to the formation of a non-uniform mixture, or the PU binder percentage was insufficient to coat all the particles (Wu et al., 2025). However, a higher PU content can still produce significant solidification efficacy, reducing the non-uniformity. This was evident after analysing the failure surface of the sample after testing (Figure 5). The poorly dispersed FA agglomerates created weak interfacial zones within the matrix, which served as stress concentration points and facilitated crack initiation during testing.

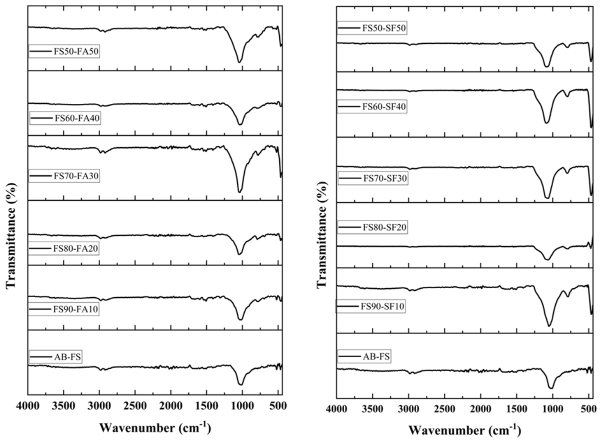

Figure 4. FTIR analysis of the WFS-FA and WFS-SF samples.

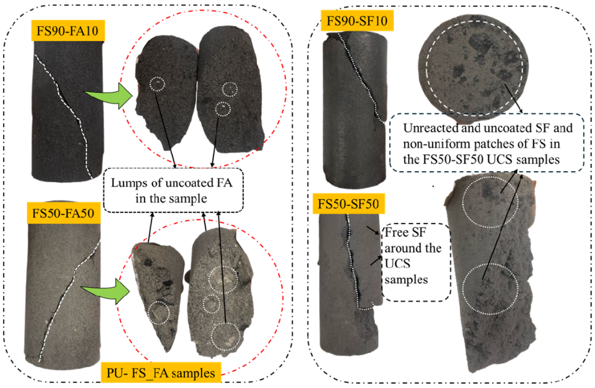

Figure 5. Figure showing the failure patterns of the samples and uncoated filler materials.

When the PU_WFS composites were included with silica fumes as the filler materials, the strength of the composite samples initially increased and then reduced. A 21% increase in strength from 11 MPa to 13.3 MPa was observed when the WFS was replaced by 10% SF. However, with the further replacement of the WFS by SF, the UCS reduced drastically. The strength was reduced by 70% when 50% of WFS was replaced by SF. When the percentages of the SF were increased in the PU_WFS composites, the silica fumes were not completely mixed with the PU binder to form a uniformly mixed network. This was visually evident when the SF started coming out from the samples, uncoated or unbound, when the UCS samples were extruded from the mould.

Moreover, when tested, the failure surface was not well-defined for the FS50-SF50 sample compared to that of the FS90-SF10 sample. The FS50-SF50 sample got powdered easily upon failure, and it could be easily identified that the SF had not completely taken part in the network formation (Figure 3 and Figure 5). This can be due to the extremely high surface area and surface energy, which caused the particles to agglomerate, forming large and irregular clusters. Moreover, adding fine powders like SF increased the viscosity of the liquid PU, making sample mixing difficult and causing the particles to remain poorly dispersed. This issue was more severe with SF than with FA due to its comparatively finer size. PU is an organic hydrophobic polymer, whereas the silica fumes have a hydrophilic surface, making it difficult for the liquid PU to wet the surface of SF particles. This low compatibility made the PU surround the existing agglomerates instead of coating and separating the individual particles.

4.2 *Effect of water submergence on UCS*

The UCS samples of the respective composites (PU_WFS-FA and PU_WFS-SF) were cast, cured for 24 hours at ambient temperature and kept submerged in the water bath maintained at room tempertaure for 28 days. Three samples in each proportions were tested and the average of three samples were reported as the UCS.

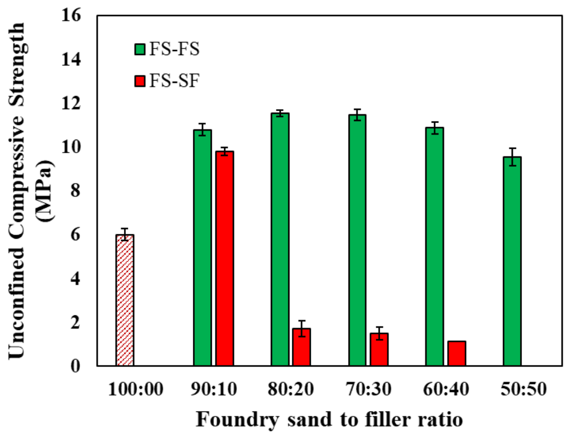

Figure 6. Effect of water submergence on the Unconfined Compressive Strength of the composites.

It can be noted that the strength of the samples reduced with the water submergence. The UCS of the PU_WFS sample reduced from 11.11 MPa to 6.01 MPa, indicating a strength reduction of 45% when submerged for 28 days. In contrast, incorporating FA as a filler significantly mitigated the deterioration in strength. The UCS was reduced by 13%, 17%, and 19% with 10%, 20%, and 30% replacement of WFS with FA, respectively. These results corroborate the earlier inference that the addition of FA helped to make the matrix denser and disrupts the water transport pathways, resulting in reduced moisture-induced strength reduction. Nonetheless, the UCS started reducing at a higher percentage of WFS replacement. The strength reduced to 10.87 MPa from 15.07 MPa (28% reduction) with 40% WFS replacement. The UCS was reduced by 42% for the FS50-FA50 sample. This pronounced loss of UCS in the sample at higher FA content suggests the formation of non-uniform and unbound sample clusters formed due to insufficient binder content, thereby paving pathways for water percolation. Prolonged water interaction of the PU reduces the strength by chemically degrading the polymeric chains. It weakens the secondary bonding (hydrogen bonds and van der Waals forces) between the PU and WFS (Pengfei et al., 2025).

The strength reduction in the PU_WFS-SF composites was more severe than that in the PU_WFS-FA composites. The strength of the FS90-SF10 sample was reduced by 26%, while the reduction in the UCS was more than 75% for all other SF containing samples. The FS50-SF50 sample crumbled within the water bath after just 1 day of submergence, indicating pronounced heterogeneity and a critical binder deficiency in the mixture.

5 CONCLUSIONS

The influence of the filler materials on the unconfined compressive strength of the polyurethane-foundry sand composite was studied by incorporating silica fumes and fly ash by replacing foundry sand in parts. The incorporation of fly ash (FA) as a filler material in polyurethane-foundry sand (PU-WFS) composites increased the unconfined compressive strength (UCS), which was directly proportional to the filler content. The UCS of the composite increased by 50% when 50% of the WFS was replaced by FA. The strength increased to 16.5 MPa from 11 MPa when 50% FA fillers were introduced. Introducing FA into the matrix reduced the void spaces between the WFS, thus increasing the bulk density and particle-to-particle friction. However, when SF was introduced as the filler, the UCS initially increased due to the improvement in the particle packaging and later got reduced by 70%. The non-uniformity in the mixing of the constituents was observed when 20% SF replaced WFS. The SF particles agglomerated due to the extremely high surface area and surface energy, forming the SF lumps throughout the samples, creating weak failure sections. Moreover, the incompatibility of the hydrophobic PU and the hydrophilic SF caused the PU to coat around the existing SF agglomerates instead of coating and dispersing the SF particles. However, this phenomenon was less pronounced with fly ash (FA) due to its comparatively larger particle size and lower specific surface area, which resulted in reduced surface-to-volume ratio. The reduction in the UCS of the PU_WFS-SF samples was higher compared to PU_WFS-FA samples, reinforcing the findings. The reduction in UCS remained below 20% up to 30% replacement of WFS with FA; however, beyond this level of replacement, the UCS decreased sharply. Thus, the increased surface area created by a greater inclusion of fine filler particles requires a higher proportion of the polyurethane (PU) binder to sufficiently coat the particles and facilitate adequate interfacial bonding, thereby producing more uniform and reliable strengths. The study was concluded based on the UCS results and requires intense research on the mixture to understand the suitability and performance for specific applications, such as embankments or pavements. Additionally, an extended curing period will enable more comprehensive evaluation of the long-term performance of the composites.

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