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Deformation Pattern of Expanded Polystyrene (EPS) and Palm Oil Fuel Ash (POFA) Concrete Subjected to Experimental Pullout Test

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Abstract

This research explores the potentials of Palm Oil Fuel Ash (POFA) and Expanded Polystyrene (EPS) as substitutes in concrete compositions, addressing sustainability and performance enhancement. POFA was utilized as a replacement for up to 20% of the cement content, while EPS replaced fine aggregate by up to 10% in the concrete mix. The study primarily assesses the deformation pattern of the modified concrete compositions subjected to the pullout test. This research focusing on the pullout capacity and pullout failure pattern of the concrete specimen, comparing their performance against conventional concrete. This investigation details a comprehensive approach, covering material selection, specimen preparation, and testing procedures for slump test, density test and pullout test. The results obtained reveal POFA's substantial contribution to concrete strength, accompanied by a reduction in slump values as the percentages of EPS and POFA increase. Notably, the integration of EPS leads to a decrease in concrete density, indicating potential benefits in reducing structural dead load. Moreover, the bonding strength is improved with the inclusion of POFA. Tension cracks observed during pullout tests are mitigated by the presence of EPS and POFA, particularly at specific replacement ratios. In conclusion, this study yields crucial insights into the bonding strength and deformation patterns of concrete with EPS and POFA, paving the way for the development of high-performance and eco-friendly concrete materials suitable for various applications in the construction industry. These findings hold significance in advancing sustainable construction practices, promoting efficiency, and contributing to the development of environmentally friendly building materials.

1. Introduction

Concrete, a fundamental building material renowned for its versatility and durability, continues to evolve with innovative additives and compositions to enhance its performance. Among these additives, the integration of Expanded Polystyrene (EPS) and Palm Oil Fuel Ash (POFA) stands out as a promising avenue, offering not only potential enhancements to structural properties but also addressing sustainability concerns within the construction industry [1, 2].

EPS, characterized by its lightweight yet resilient cellular structure, and POFA, a by-product of the palm oil industry, have individually shown promising attributes in concrete. EPS contributes to reducing density and thermal conductivity, while POFA offers pozzolanic properties, augmenting concrete strength and durability [3, 4].

However, understanding the intricate behavior of concrete compounded with EPS and POFA under various loading conditions remains a critical area of research. Specifically, the deformation patterns and mechanical responses of such composite concrete structures to pullout forces have not been extensively explored.

This research endeavors to bridge this gap by conducting a series of experimental pullout tests meticulously designed to elucidate the deformation patterns exhibited by EPS and POFA-incorporated concrete. Through comprehensive analysis and observation of these tests, the study aims to delineate the maximum pullout capacity, failure mechanisms, and the interplay of EPS and POFA within the concrete matrix.

Unraveling the deformation patterns and failure mechanisms of EPS and POFA-infused concrete under pullout forces holds significant implications for optimizing structural designs and advancing sustainable construction practices.

1.1 Expanded Polystyrene (EPS)

Expanded Polystyrene (EPS) has a significant history in civil construction, notably in lightweight aggregate concrete, and the concept of a circular economy has driven the use of waste EPS as a filler in lightweight concrete, aligning with sustainability goals [5]. While EPS is commonly used in structural applications, its utilization in non-structural polystyrene concrete, particularly from waste EPS, remains an underexplored area in research [5]. This form of concrete offers promises for non-structural elements like walls and slabs, providing lightweight, cost-effective construction with improved insulation and sustainability benefits [6]. EPS properties, stemming from its closed-cell structure, include low density, thermal insulation, hydrophobicity, and resistance to various chemical agents, making it a desirable material in construction [7]. Recognized initially for packaging, EPS has evolved into a crucial construction material, contributing to green building designs by enhancing energy efficiency, indoor environmental quality, and structural durability [6].

Fig. 1 *Expanded Polystyrene (EPS)*

1.2 Palm Oil Fuel Ash (POFA)

The burgeoning demand for concrete has fueled interest in sustainable alternatives to mitigate its environmental impact. Palm Oil Fuel Ash (POFA), an abundant agricultural byproduct from palm oil production, is gaining attention as a Supplementary Cementitious Material (SCM) for concrete. POFA, with an annual global production of 12 million tonnes, offers potential to reduce CO2 emissions linked to conventional cement production. Studies highlight its ability to enhance concrete sustainability by improving strength, durability, and reducing shrinkage. Despite potential drawbacks like increased water absorption and delayed hydration, treated POFA particles exhibit improved concrete properties due to their high silicon dioxide (SiO2) content, triggering pozzolanic reactions [8]. The particle fineness of POFA significantly impacts its performance, influencing concrete strength through enhanced interaction with cement [9]. Chemically, POFA is rich in amorphous silica (SiO2) and trace elements, contributing to its cementitious characteristics and long-term strength [10]. Treatment methods to remove residual carbon particles from POFA optimize its compatibility with superplasticizers, ensuring improved performance in concrete production [11].

Fig. 2 *Palm Oil Fuel Ash (POFA)*

1.2.1 X-Ray Diffraction (XRD) of POFA

The investigation into the silica structure of Palm Oil Fuel Ash (POFA) involved the utilization of X-Ray Diffraction (XRD) testing. XRD is a non-destructive analytical method crucial for elucidating the crystalline structure of materials. It enables the identification of crystalline phases within a substance and offers detailed insights into its chemical composition by examining the arrangement of its crystals. This technique utilizes X-rays to interact with the atomic structure of the material, producing diffraction patterns that are then analysed to determine the crystalline properties, crystal sizes, and lattice structures present in the POFA, aiding in understanding its composition and properties [12].

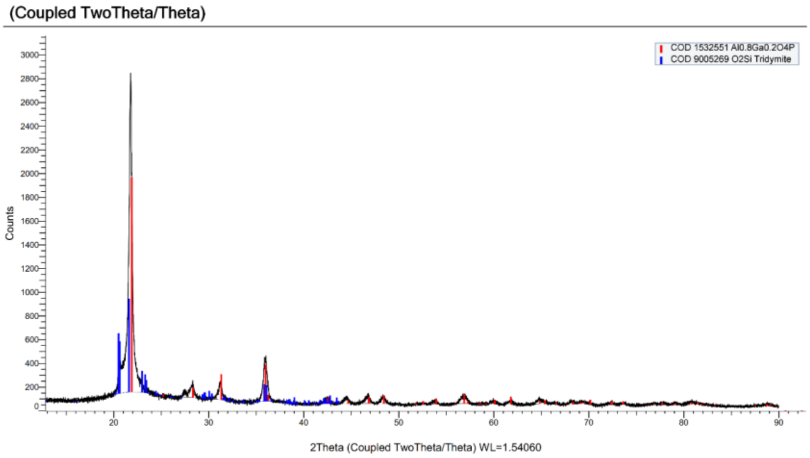

Fig. 3 *X-Ray Diffraction Spectrum of POFA*

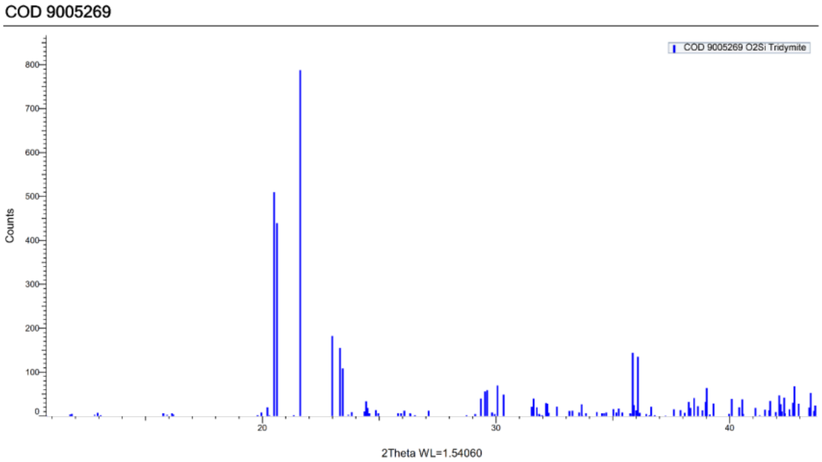

Fig. 4 *Tridymite (SiO2) of POFA*

The XRD pattern of POFA shows broad peaks, indicating the presence of amorphous phases, particularly a broad hump between 20° to 30°, suggesting the presence of amorphous silica (SiO2) in the material. This amorphous form of silica is significant in promoting the pozzolanic reaction, a key factor contributing to the strength of concrete. Initially, the XRD pattern displays some small peaks identified as crystalline silica, which might indicate the presence of crystalline phases like Tridymite (classified as silica dioxide) and aluminium compounds. These crystalline phases coexist with the amorphous silica in the POFA. The combination of amorphous silica and aluminium in POFA can lead to the formation of secondary hydration products when incorporated into concrete. This process positively impacts the microstructure of concrete, enhancing its compressive strength. In summary, the XRD analysis of POFA reveals the presence of amorphous silica and crystalline phases. The amorphous silica plays a significant role in enhancing the pozzolanic activity, contributing to the strength improvement of concrete [13].

1.3 Concrete

Concrete is frequently employed as a key structural element in construction due to its many benefits over other building materials, including strength, durability, ease of manufacture, and non-combustibility [14]. Concrete is a reliable material for buildings, roads, bridges, and dams due to its capacity to support enormous weights and withstand environmental elements including weathering and fire. Its versatility in terms of building methods, such as precasting or on-site pouring, further enhances its practicality [15]. Additionally, adding steel bars or fibres to concrete strengthens it so that it can withstand bending and stretching forces. With the growing importance of sustainability, attempts are being made to create eco-friendly concrete by utilising recycled resources and alternative cementitious solutions.

1.3.1 Bonding Strength Between Steel and Concrete

The performance of reinforced concrete relies on how its components, steel and concrete, interact. This bond is crucial and can fail in various ways, including pure pullout or push-in, and splitting of the concrete cover. The pullout test, commonly used to assess short bond lengths, can also be adapted to a push-in setup for smaller bar diameters, particularly useful in studying impact loading behavior [16]. Studies indicate that concrete and reinforcing steel tend to strengthen under high-loading rates, known as the strain rate effect. However, this effect differs between concrete's compressive and tensile strengths [17, 18, 19]. To ensure structures, like nuclear power plants or rockfall galleries, can withstand impact, it's vital that the bond between concrete and steel can handle these forces as well [16].

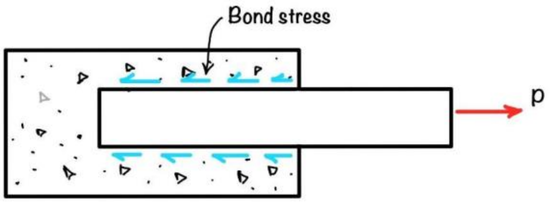

Fig. 5 *Bonding Strength Between Steel and Concrete*

1.3.2 Types of Cracking in Reinforced Concrete Structure

i. Cracks from tension:

When a reinforced concrete element is subjected to axial tension or tension due to small eccentricities, cracks form perpendicular to the direction of the force. These cracks are a result of operational loads or thermal shrinkage. For instance, in structures like reinforced concrete trusses, strings, or cylindrical walls of liquid tanks, these cracks emerge due to tensile forces (N) generated within the cross-sections of the elements.

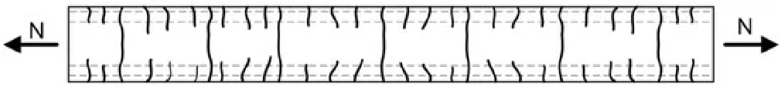

Fig. 6 *Tension Cracks*

ii. Cracks from bending:

Bending causes tensile stresses at specific points in the concrete cross-section, leading to cracks that tend to occur before the zone of zero tensile stresses. In heavily reinforced elements, both single perpendicular cracks or collective cracks can be observed. These cracks may have various patterns, including single or slightly curved cracks in typical cases.

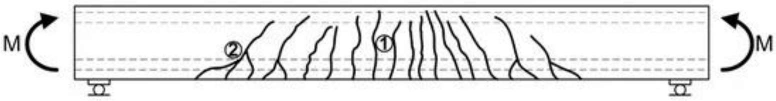

Fig. 7 *Bending Cracks*

iii. Cracks due to shear:

Shear-induced cracks result from inclined main tensile stresses due to the combined impact of transverse forces (V) and bending moments (M). In areas with limited transverse force influence, cracks perpendicular to the beam axis appear. However, in support zones where transverse forces dominate, diagonal cracks (inclined to the longitudinal axis) develop. Often, these cracks may evolve from previously formed bending-induced cracks.

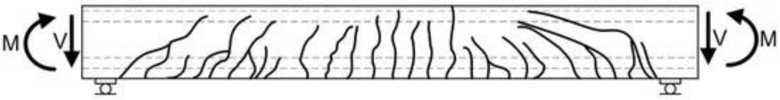

Fig. 8 *Shear Cracks*

iv. Cracks due to torsion:

Torsion in reinforced concrete elements, a less common scenario, induces shear stress in the sections due to torsional moments (T). These stresses cause cracks that form a characteristic helix shape, inclined at a 45° angle to the element's axis. These cracks initially start on one side surface along the longer edge of the cross-section, eventually spreading to other surfaces as the load increases. This distinguishes torsion-induced cracks from shear-induced ones, where cracks occur only on the side surface of the beam [20].

Fig. 9 *Torsion Cracks*

1.4 Pullout Test

The pullout test stands out as a significant method for assessing concrete strength, involving the extraction of a small concrete cone embedded with an anchor to measure the force required for removal, distinguishing it from indirect techniques like the rebound hammer. It's highly regarded in non-destructive testing due to its accuracy in estimating in-situ concrete compressive strength, especially in field scenarios where potential strength might not be pertinent, as outlined in British Standards BS 1881: Part 207 [21]. While it's considered one of the most reliable NDT procedures for concrete strength assessment, it comes with drawbacks, causing surface damage and requiring expensive measuring tools. Construction engineers and inspectors primarily aim to use NDT methods like the pullout test to ascertain whether structural concrete components meet or exceed the specified target strength [22].

Fig. 10 *Pullout Test*

1.4.1 Failure Mechanism in Pullout Test

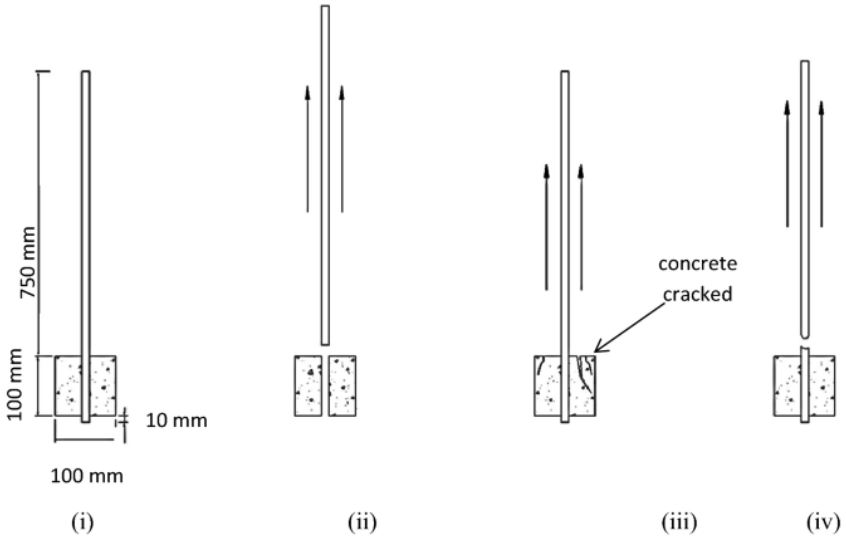

Fig. 11 *Failure Mechanism in Pullout Test (i) Original Specimen; (ii) Pullout Failure of the Steel Bar from Concrete; (iii) Splitting Failure of Concrete; (iv) Rupture of the Reinforcement Bar*

a) Pullout Failure of the Steel Bar from Concrete (**Fig. 10**-ii): This failure happens when the bond between the steel bar and concrete is stronger than the concrete's shear strength. In such cases, the surrounding concrete prevents significant cracking or splitting. It shows that the bond between the steel and concrete is strong enough for the bar to be pulled out without causing major damage.

b) Splitting Failure of Concrete (**Fig. 10**-iii): This occurs when tensile stress in the concrete exceeds its shear capacity, resulting in wider cracks within the concrete. These cracks extend toward the surface due to tension, possibly caused by forces on the steel bar or anchor. Different factors like anchor type, concrete properties, and dimensions affect this mode, making it complex to isolate individual influences.

c) Rupture of Reinforcement Bar (**Fig. 10**-iv): This failure happens when the bar itself breaks instead of the concrete. It can occur due to excessive load surpassing the bar's tensile strength, or when the bar is weaker than the surrounding concrete. Bar quality, defects, corrosion, or environmental factors can also contribute. This failure emphasizes the need for using strong and suitable reinforcement bars for expected loads and conditions [23].

2. Methodology

2.1 Concrete Mix Design (BS DoE Method)

In this study, the British Design of Experiments (DoE) method, is employed aligning with British Standards in designing the concrete mixture. This approach entails precise steps: determining the w/c ratio, computing free water content and cement volume, ascertaining aggregate volumes (both fine and coarse), accommodating moisture in aggregates, and finalizing proportions. Key parameters influencing concrete properties, including strength, slump, air content, cement content, and the w/c ratio, are influenced significantly by the quality of materials employed, such as cement and aggregates. These pivotal mix design considerations are essential for producing optimal concrete performance. The water cement ratio used in this study is 0.6.

2.2 Replacement Ratio of EPS and POFA

In this study, the concrete specimen is constructed with different replacement ratios of EPS and POFA for subsequent laboratory testing. Eight 100mm x 200mm cylinder samples are constructed for each replacement ratio as shown in Table 3.1. EPS replace from 0% up to 10% of the fine aggregate by volume in the concrete mixture, whereas POFA replaces from 0% up to 20% of the cement by weight. The sample with 0% of EPS and POFA is constructed for reference purpose to compare with concrete with EPS and POFA.

Table 1 *Quantity of Concrete Cylinder Samples*

EPS	0%	10%
POFA 0%	8	8
POFA 10%	8	8
POFA 20%	8	8

2.3 Concrete Cylinder Specimen

Each concrete cylinder specimen in this study has dimensions of 100mm radius and 200mm height. These specimens will undergo a curing period of 28 days to allow for the development of their mechanical properties. Three concrete specimens are designed without reinforcement bar and one concrete specimen is embedded with 300 mm high strength deformed reinforcement bar.

Table 2 *Detail of Concrete Cylinder Samples*

Percentage of POFA	Percentage of EPS (%)	Density of Material (kg/m^3)						Number of Cylinder	
		Cement	POFA	Fine Aggregate	EPS	Coarse Aggregate	Water	7 Days	28 days
0%	0	320	0	405.0	0.00	1440	160	3+1	3+1
	10	320	0	364.5	0.54	1440	160	3+1	3+1
10%	0	288	32	405.0	0	1440	160	3+1	3+1
	10	288	32	364.5	0.54	1440	160	3+1	3+1
20%	0	256	64	405.0	0.00	1440	160	3+1	3+1
	10	256	64	364.5	0.54	1440	160	3+1	3+1
TOTAL SAMPLE								48	

3. Result and Discussion

3.1 Slump Test

Table 3 *Slump Test Results*

POFA	EPS	Slump (mm)
0%	0%	24
	10%	20
10%	0%	15
	10%	13
20%	0%	6
	10%	5

The slump test, conducted to assess concrete workability, revealed results outside the Design of Experiments (DoE) method's allowable range of 30–60 mm. As the proportion of POFA and EPS increased in the concrete mix, the slump values consistently decreased. Specifically, the inclusion of 10% POFA led to a 36.25% reduction in slump, while 20% POFA resulted in a 75% decrease. Similarly, the addition of 10% EPS led to an average 15.56% decrease in slump. These reductions in slump values suggest a significant impact on concrete workability due to higher POFA and EPS percentages. This deviation from the expected slump range prescribed by the DoE method indicates potential alterations in essential aspects of the concrete mix beyond the intended parameters.

3.2 Density Test

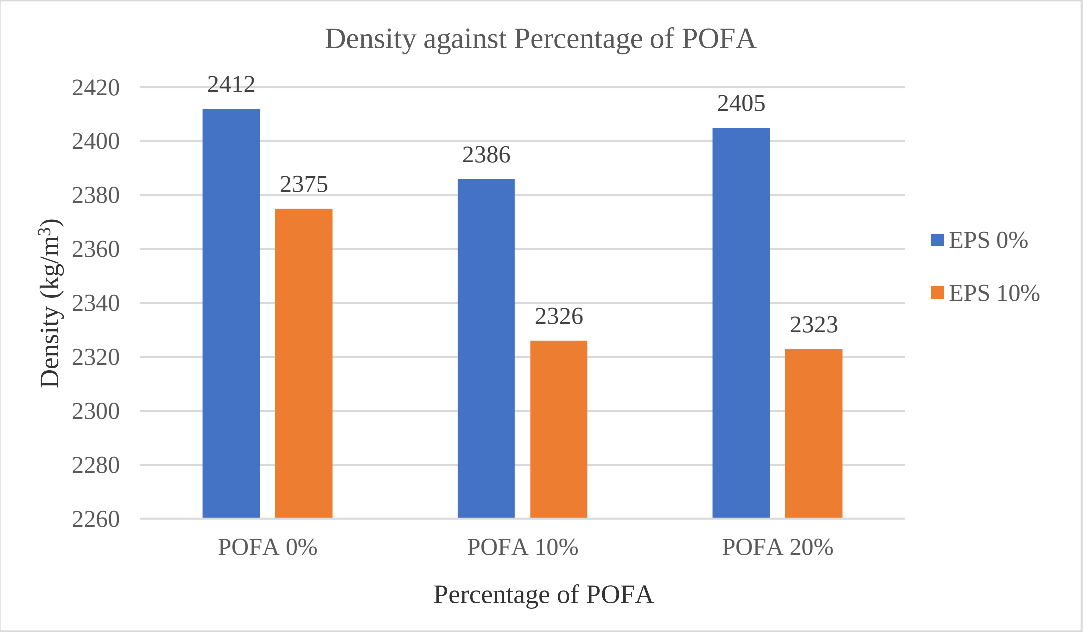

Fig. 12 *Bar Chart of Density against Percentage of POFA*

The bar chart illustrates a noticeable decrease in concrete density as the percentage of EPS and POFA increases, reaching a minimum of 2323 kg/m3 compared to the control ratio of 2412 kg/m3. This decrease of 89 kg/m3, approximately 3.7% less than normal concrete, is primarily attributed to the lightweight properties of EPS. Substituting fine aggregate with EPS reduces the overall weight of the concrete while maintaining adequate strength. This density reduction directly lessens the dead load of the concrete structure, offering advantages in construction by optimizing load distribution and enhancing structural integrity. Consequently, incorporating EPS and POFA in concrete formulations leads to lower density compositions, thereby reducing the dead load and improving overall structural efficiency [1].

3.3 Pullout Capacity

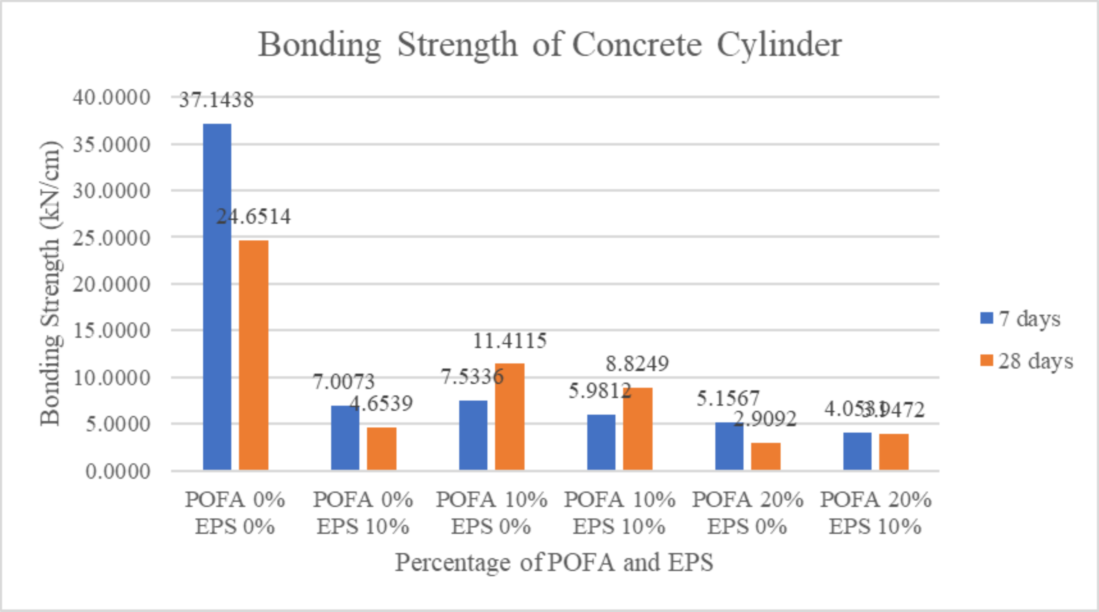

Fig. 13 *Bar Chart of Bonding Strength of Concrete Sample*

The graph displays the bonding strength of concrete subjected to pullout tests. Concrete with POFA replacements shows higher bonding strength compared to other replacement ratio of concrete mixture, except for the control specimen. The control mixture (0% EPS, 0% POFA) demonstrates the highest bonding strength, reaching 37.14 kN/cm at 7 days and 24.65 kN/cm at 28 days. Whereas 10% POFA-containing mixes, exhibit second highest bonding strength at 7.53 kN/cm at 7 days and 11.41 kN/cm at 28 days. The trend that concrete mixtures that containing POFA, especially at 10%, showing the highest bonding strength among other replacement ratio suggests that POFA enhances bonding between concrete and reinforcement bars. This improvement is credited to POFA's pozzolanic properties, as it reacts with calcium hydroxide during cement hydration, forming additional C-S-H gel. The amorphous silica in POFA aids this reaction, leading to denser and better-connected interfaces between the concrete and reinforcement. This densification strengthens the bond, reduces micro-cracks, and improves load transfer, ultimately enhancing the concrete's ability to withstand pullout forces [24].

The disparity in bonding strength between the control specimen and the concrete with POFA and EPS is linked to a crucial aspect of the experimental methodology. The use of untreated POFA in this study indirectly affected its bonding capacity due to residual impurities and unprocessed particles. These elements hindered the formation of a robust bond between the concrete matrix and the embedded reinforcement, potentially reducing bonding strength [25]. Recognizing the untreated nature of the POFA used is vital, as it significantly influenced the observed results. Future studies could benefit from using treated or processed POFA to address this issue and ensure a more accurate assessment of the bonding capabilities in concrete mixtures.

3.4 Deformation Pattern of Concrete Subjected to Pullout Test

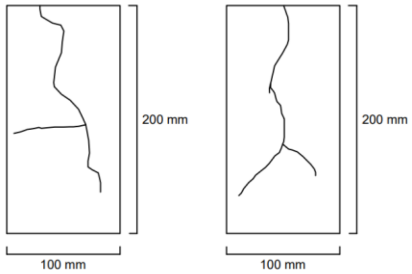

Fig. 14 *Cracking Pattern of Concrete with 10% POFA*

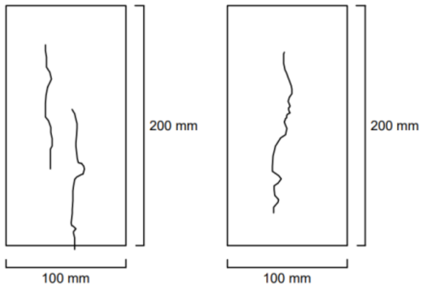

Fig. 15 *Cracking Pattern of Concrete with 10% POFA 10% EPS*

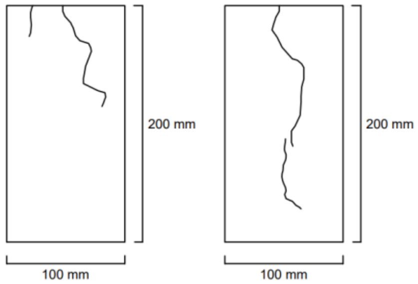

Fig. 16 *Cracking Pattern of Concrete with 20% POFA 10% EPS*

In this research, an unintentional deviation occurred in the data collection process for determining the size of cracks in concrete cylinders subjected to the pullout test. Due to an oversight, actual crack dimensions were not directly measured; instead, they were visually estimated based on experimentation. While this method allowed for qualitative analysis, it lacked the precision of direct measurement techniques, impacting exact quantification. It is crucial to openly acknowledge this limitation, suggesting that future studies could benefit from refined methodologies for more accurate measurements of crack sizes, enhancing understanding of concrete behavior under pullout tests. Despite this limitation, the study provides valuable qualitative insights into crack patterns, indicating potential areas for improvement in future research methodologies.

The testing revealed a consistent occurrence of concrete splitting failure across all samples, indicating tension surpassing the concrete's shear capacity and resulting in surface cracks. During the pullout test, the force applied generated tension, causing cracks along the concrete's axis. However, samples containing POFA, especially at 10% and in combinations with EPS, displayed smaller surface cracks, suggesting POFA's role in minimizing crack size. This effect relates to POFA's pozzolanic characteristics, filling voids, improving the concrete's structure, and reducing crack propagation [26]. Additionally, EPS aided in limiting crack expansion by creating internal reinforcement and absorbing stresses. Ultimately, the incorporation of POFA and EPS appears crucial in reducing crack size and enhancing the concrete's durability by limiting crack propagation.

4. Conclusion

Replacing POFA with cement notably increases bonding strength, especially evident in the 10% POFA mix. Tension-induced cracking on the concrete surface during pullout tests was observed. Notably, combinations of EPS and POFA helped mitigate crack sizes, particularly in specimens with 10% POFA and 10% EPS. Overall, these findings underscore the significant influence of EPS and POFA on concrete properties, offering insights for optimizing concrete formulations in construction applications.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

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Journal

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