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Bonding strength of steel and concrete containing Palm Oil Fuel Ash (POFA) and Expanded Polystyrene (EPS)

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ABSTRACT

The usage of recycled materials in concrete has become popular recently. This paper focuses on a study related to the bonding between steel and concrete containing expanded polystyrene beads (EPS) and palm oil fuel ash (POFA) as replacement material. The EPS were used as fine aggregate replacement, and POFA was used as cement replacement. The replacement percentages for EPS and POFA in the concrete were limited to a range of 0-30% and 0-10%, respectively. Previous studies have identified the potential of POFA and EPS as concrete substances. The typical issue with EPS-containing concrete is its characteristic weakness, which leads to a compromised bond with steel. This occurs because EPS fails to effectively interact with cement, resulting in a weak bond and low compressive strength. Consequently, in this study, POFA is introduced as an addition to enhance the bond strength between EPS-containing concrete and steel. Pull-out tests in this study seem to represent the bonding performance between concrete and steel. The 10% of POFA in concrete seems might improve its performance in terms of compression strength, and bonding between concrete and steel.

Keywords: *Palm oil fuel ash, Expanded polystyrene beads, Steel and concrete bonding strength*

1. INTRODUCTION

In recent years, the construction industry has witnessed a growing interest in developing innovative and sustainable building materials to meet the demands of modern construction practices. Concrete, the backbone of construction, has been the subject of extensive research and development to enhance its performance characteristics. Among the numerous approaches, incorporating Expanded Polystyrene (EPS) beads and Palm Oil Fuel Ash (POFA) as additives in concrete has emerged as a promising avenue. Thus, lighter, better performing, and environmentally friendly concretes are needed to cater to the demand [1]. EPS, a solid cellular plastic known for its lightweight and thermal insulation properties, has found applications in various industries, including construction. When added to concrete, EPS beads create a composite material that offers reduced weight and improved thermal performance. This lightweight concrete not only conserves resources during construction, but it also reduces transportation costs and improves the overall energy efficiency of buildings [2].

On the other hand, POFA, a byproduct of palm oil production, has attracted attention as a potential supplementary cementitious material due to its high silica content and pozzolanic characteristics. Incorporating POFA in concrete not only contributes to sustainable waste management but also enhances concrete's mechanical and durability properties, making it a viable solution for eco-conscious construction [1]. One of the main problems with concrete containing EPS is its pull-out strength. EPS beads' lower density than the concrete matrix can lead to insufficient anchoring when subjected to loads or stresses, potentially causing debonding or pull-out failure. To enhance the pull-out strength of concrete containing EPS, this study has explored modified concrete mixtures with specific admixtures or binders that promote better bonding between EPS and concrete. Additionally, POFA a waste product with high silicon dioxide (SiO_2) content, has been utilized as an admixture in concrete, showing the potential to enhance pull-out strength [1]. Previous research indicates that concrete with 10–30% POFA exhibited higher compressive strength than control concrete at various curing periods [1,3,4].

1.1. Utilization of POFA and EPS in Concrete

The utilization of POFA and EPS as eco-friendly materials in concrete has gained significant attention in both academic research and the industry. Previous studies have demonstrated that replacing cement with POFA results in concrete with equal or greater strength than conventional concrete. POFA is rich in silica, alumina, and calcium, contributing to the formation of cementitious compounds in the concrete mixture. Conversely, EPS serves as lightweight aggregates in concrete production, allowing for the creation of concrete with varying densities when combined with other materials like POFA in mortar or concrete [5].

Based on the comprehensive review, it can be inferred that replacing sand with EPS and cement with POFA in concrete offers numerous advantages. These benefits include increased concrete strength, reduced density, enhanced workability of fresh concrete, and reduced water absorption. Moreover, this approach contributes to environmental preservation by reducing the dependence on natural resources and decreasing industrial waste generation. To achieve a consistent and well-established mix design, this study adopts replacement percentages for EPS and POFA ranging from 10% to 30% in light of the positive performance observed in prior research. The research employs the Design of Experiments (DOE) method to achieve this goal [6].

1.2. Pull-out Test on Concrete containing EPS and POFA

The current study did not find any specific research papers or studies that directly investigated the Pull-out test or bonding strength between steel and concrete containing EPS and POFA. Nonetheless, it is essential to note that the bonding strength can be influenced by the concrete mix design, encompassing the appropriate proportions of cement, aggregates, and additives such as EPS and POFA. A meticulously planned mix, with a well-balanced combination of these materials, has the potential to enhance the bond between concrete and steel [7].

1.3. Expanded Polystyrene Beads (EPS)

EPS serves as a versatile material used for packaging and insulation purposes. It possesses an extremely low density, with EPS primarily composed of approximately 2% polystyrene and 98% air. The expansion process ensures that the beads do not absorb water, making them ideal for use as a lightweight aggregate in lightweight concrete. This type of EPS is a stable foam characterized by low density and consists of discrete air voids embedded within a polymer matrix. Lightweight concrete can be produced by easily incorporating polystyrene beads into mortar or concrete, offering a wide range of densities [8]. In the past, including polystyrene beads in concrete led to segregation issues due to the untreated beads' extreme lightness and hydrophobic nature [9].

1.4. Palm Oil Fuel Ash (POFA)

Several studies have highlighted the favorable pozzolanic properties of oil palm ash, making it a suitable cement additive [10]. As a result, recycling palm oil waste not only addresses environmental pollution concerns, but also contributes to the construction industry's sustainability. POFA typically has a gray and darker appearance, with elevated levels of non-combustible carbon. While the particles vary in size, they are generally considered to have a specific gravity lower than regular Portland cement [11]. Moreover, the particle size of palm oil ash is smaller, and its texture is porous compared to the particle size of Portland cement [1,11].

2. MATERIALS AND METHODS

This section presents a comprehensive overview of the methods and materials employed in this project. The information encompasses all aspects of the testing procedure, along with the diagrams used to conduct the study. The materials utilized in this research comprised ordinary Portland cement in compliance with BS12: 1991 standards [13], sand with a fineness modulus of 2.85, crushed granite with a maximum size of 20 mm, POFA, and EPS. The EPS utilized primarily consisted of 3.0 mm size beads.

2.1. Materials

The current study conducted tests on normal-strength concrete designed to have a compressive strength of 25 MPa. The concrete mix was formulated using the DOE method as a guideline [14] he concrete composition primarily consisted of cement, fine aggregate, coarse aggregate, POFA, EPS, and water, which were the key components under investigation in this research. In the experimental setup, EPS replaced the fine aggregate, while POFA substituted for cement. The replacement percentages for EPS and POFA in the concrete were limited to a range of 0-30% and 0-10%, respectively. The dimensions of the pull-out test specimens were 500 mm × 250 mm × 250mm, with each side of the concrete cube measuring 100 mm. To ensure uniformity among the various specimens, the raw materials for the experiments were standardized. Table 1 provides detailed information on the specimens and the materials used in their composition.

2.2. X-ray Diffraction (XRD) Test

The silica structure of POFA was investigated and determined through the utilization of X-ray diffraction (XRD) testing. XRD is a non-destructive analytical method employed for studying the structure of crystalline materials. It allows for the detection of crystalline phases present in a material and provides valuable information about its chemical composition through the analysis of its crystal structure. The XRD analysis for this study was conducted in the laboratory of the Faculty of Applied Sciences and Technology at UTHM Pagoh, as depicted in Figures 1 and 2.

Table 1. Details materials used

Material	Details	Quantity
Cement	OPC	320 (kg/m^3)
Water	w/c: 0.5	160 (kg/m^3)
EPS	Size: 2 mm	0-30%
POFA	Size: 300 mm	0-10%
Fine Aggregate	Size: <5mm	405 (kg/m^3)
Coarse Aggregate	Size: 5 mm-20mm	1440 (kg/m^3)
Steel Bar	Type: Y12	0.25 m

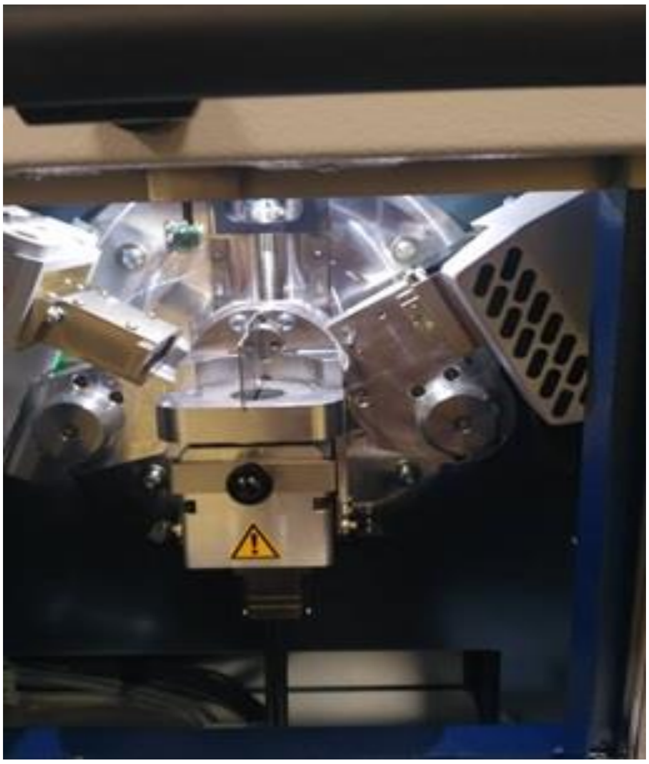

Figure 1. XRD Machine

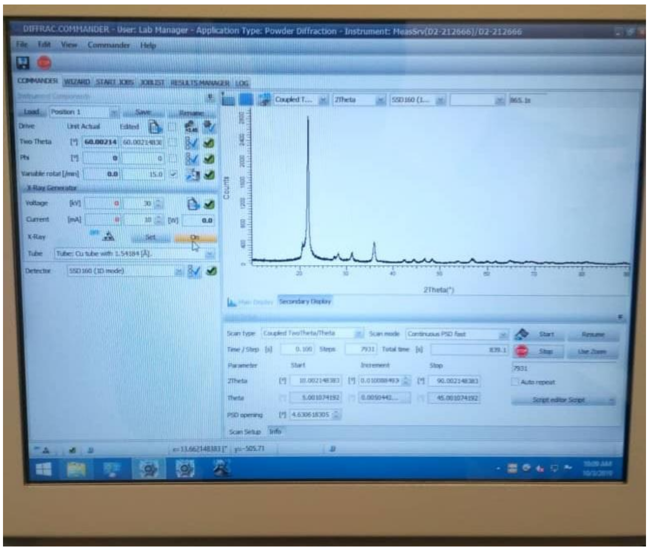

Figure 2. XRD Machine Result Processing

2.3. Compression Cube Test

Commonly, the compression test is employed to assess the concrete's strength and ensure it meets the required concrete grade. The test yields varied results depending on the concrete's maturity. For the compressive strength test, concrete cube samples were subjected to failure through compression. The testing was conducted after the samples had been cured for both seven and twenty-eight days, respectively, adhering to the guidelines outlined in BS1881-116 (1983) Method for determining the compressive strength of concrete cubes [15]. The maximum force applied to each sample was recorded. The concrete cube sample's compressive strength was determined by dividing the maximum load it withstood by its cross-sectional area. A total of 32 cube 100 mm × 100 mm samples were prepared, comprising mixes with 0% POFA and varying proportions of EPS (0%, 10%, 20%, and 30%). Furthermore, another set of 32 100 mm × 100 mm samples was prepared with 10% POFA mixed with the same EPS proportions (0%, 10%, 20%, and 30%).

2.4. Pull-out Test Method and Procedure

The concrete mould used for the pull-out test, referred to as the "steel rig," was constructed with dimensions of 250 × 250 mm × 500mm, utilizing steel, as recommended in a prior study by [16], as depicted in Figure 3. Subsequently, concrete formworks were prepared, as showed in Figure 4. Following this, concrete samples were produced, and subsequently positioned within the steel rig, as indicated in Figure 5. Finally, the pull-out test was conducted by using Universal Testing Machine (UTM) at Structures and Materials Laboratory of the Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia (UTHM), as demonstrated in Figure 6. A total of 32 concrete samples for the pull-out test were prepared, consisting of mixes containing 0% POFA and varying proportions of EPS (0%, 10%, 20%, and 30%). Additionally, another set of 32 samples was created, comprising mixes with 10% POFA combined with the same EPS proportions (0%, 10%, 20%, and 30%).

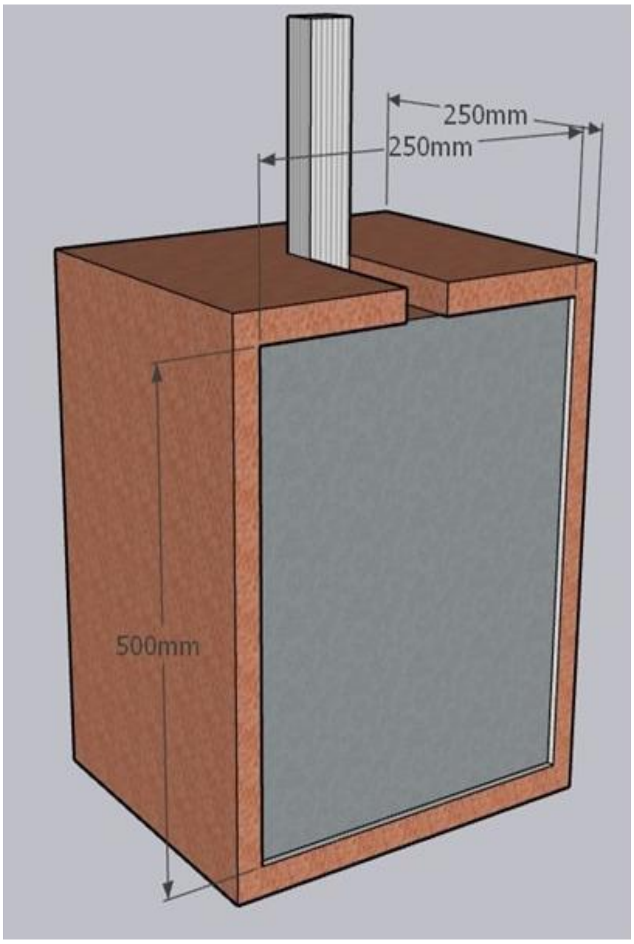

Figure 3. Pull-out test mould

Figure 4. Steel in concrete sample

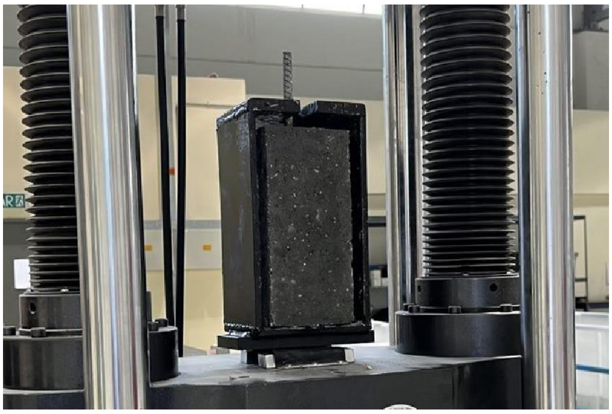

Figure 5. Concrete sample placed in steel rig

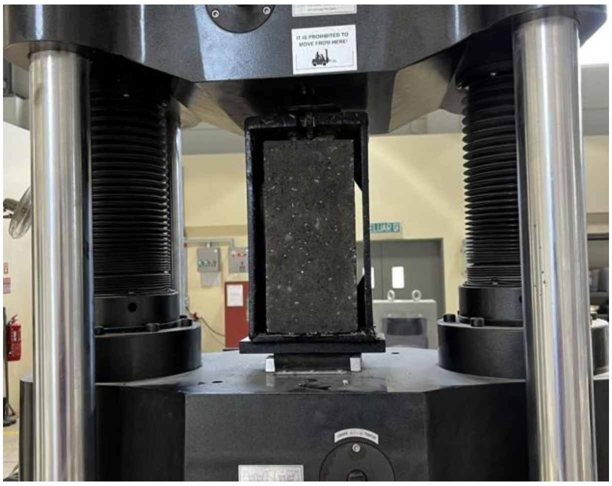

Figure 6. Pull-out test executed by using Universal Testing Machine (UTM)

3. RESULTS AND DISCUSSION

After conducting the experiments, all the data were meticulously recorded for analysis. The analysis was based on the varying percentages of POFA and EPS. As mentioned earlier, a total of 64 samples were prepared, each containing different volumes of POFA and EPS. Specifically, 32 samples were mixed with 0% POFA and varying proportions of EPS (0%, 10%, 20%, and 30%). Another set of 32 samples included 10% POFA combined with the same EPS proportions (0%, 10%, 20%, and 30%). The results were subsequently categorized into two aspects: compressive strength and pull-out strength performance.

3.1. Chemical Composition in POFA

In previous research study by Karim *et al.* (2013), it was observed that all of the pozzolanic waste products contained a high percentage of silicon dioxide or aluminum silica in amorphous form [17]. The XRD pattern of the tested POFA sample is presented in Figure 7. Information obtained from the Crystallography Open Database (COD) indicates that COD 9005269 Tridymite is classified as SiO_2, and COD 1532551 is classified as aluminum. The spectra in Figure 8 exhibit broad humped peaks, suggesting an amorphous nature. In Figure 8, the XRD spectra were separated to highlight SiO_2 as a distinct peak. The amorphous phase of POFA is represented by the flaw hump (halo) of silica between 20° to 30° on the XRD diffract grams. The combination of silica and aluminum in POFA may lead to the formation of secondary hydration products. This process improves the concrete's microstructure and enhances its compressive strength, as mentioned by Thomas *et al.* (2017) [11]. Initially, POFA's XRD pattern exhibits crystalline phases, with only a few small peaks identified as crystalline silica. The pozzolanic activity of POFA can be attributed to the presence of amorphous silica (Si). The obtained pattern also indicates that amorphous Si contributes to the concrete's strength. This finding aligns with the study conducted by Chandara *et al.* (2011) [18] which emphasized the significance of POFA's amorphous form in promoting the pozzolanic reaction.

3.2. EPS-POFA Concrete Strength

The compression strength was determined by dividing the maximum load, also known as the failure load, by the sample's area in the compression test. The concrete cube tests were conducted on specimens with dimensions of 100 mm × 100 mm × 100 mm. The compression strength measurements were taken at different maturity periods. The results of the compression test are presented in Figure 9.

The compressive strength of normal concrete, which contained 0% POFA and 0% EPS, was measured to be 25.12 MPa after 7 days and 27.69 MPa after 28 days. However, for concrete cubes containing 0% POFA with 10% EPS, 20% EPS, and 30% EPS, the compressive strength after 28 days was found to be 26.30 MPa, 25.17 MPa, and 24.19 MPa, respectively. It was observed that with an increase in the percentage of EPS from 10% to 30%, the compressive

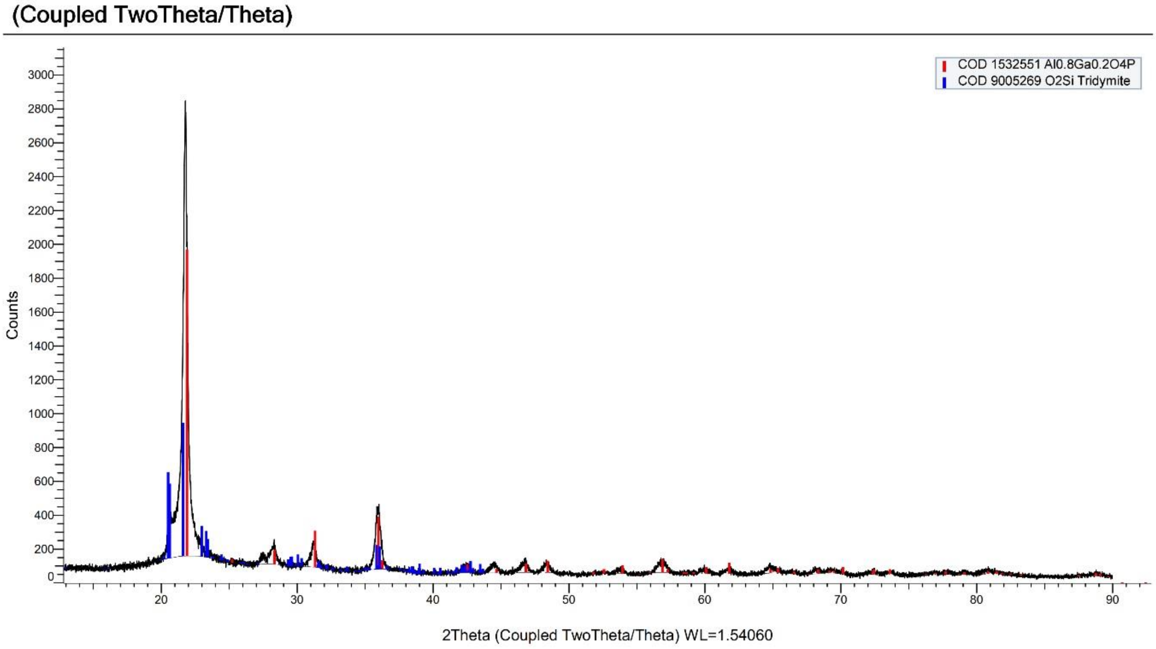

Figure 7. XRD spectrums for POFA

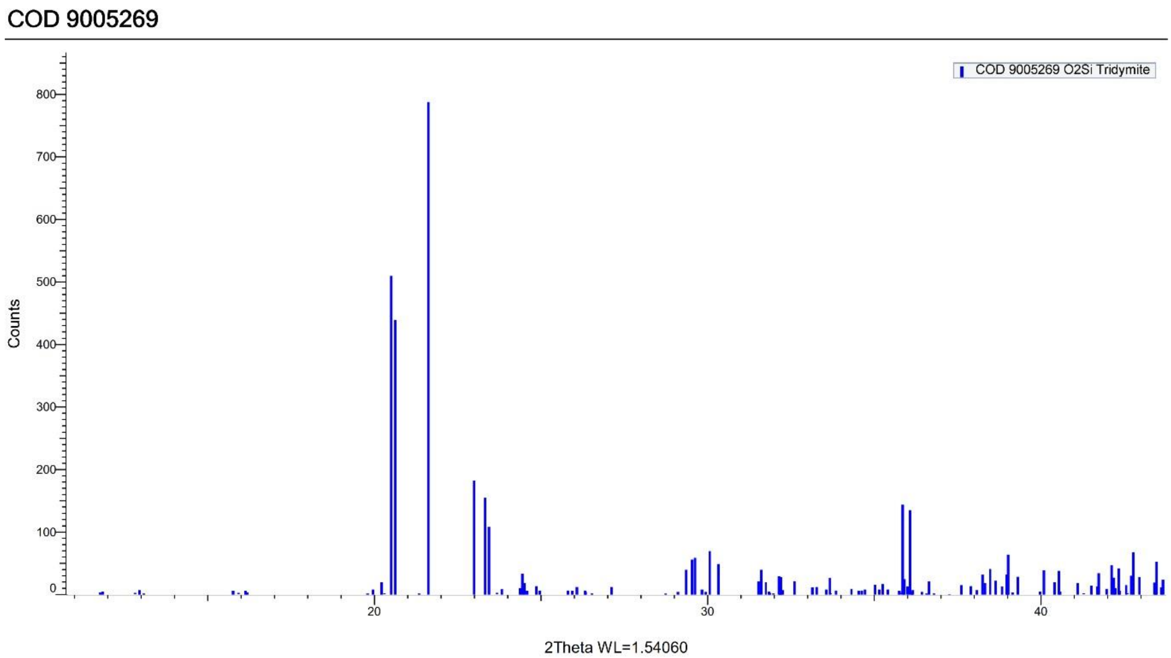

Figure 8. SiO_2 Tridymite of POFA

strength of the concrete cubes decreased both at 7 and 28 days. This reduction in strength with higher EPS content is in agreement with the findings of Nikbin & Golshekan (2018) [19], who reported a decrease in compressive strength with increased EPS content. The compressive strength of concrete containing EPS and POFA is compared after 7 and 28 days to observe the trend in concrete strength during the early stage (at 7 days) and the ultimate stage (at 28 days).

The lower strength and stiffness of the EPS aggregate, compared to natural aggregates, are considered the primary reasons for the drop in compressive strength when more EPS is added. Additionally, the presence of EPS in the concrete increases the surface area, resulting in a weak transition zone between the cement paste and the aggregate.

Interestingly, the concrete with 10% POFA without EPS exhibited a slight increase in compressive strength, measuring 27.50 MPa after 7 days and 29.66 MPa after 28 days. This compressive strength was higher than that of normal concrete, showing a 1% increase for 10% POFA compared to the normal concrete. The higher compressive strength of concrete with 10% POFA is attributed to the relatively higher silica content in the POFA used in this study, as revealed in the Micro XRD test results. The pozzolanic reaction of the 10% POFA in the concrete likely

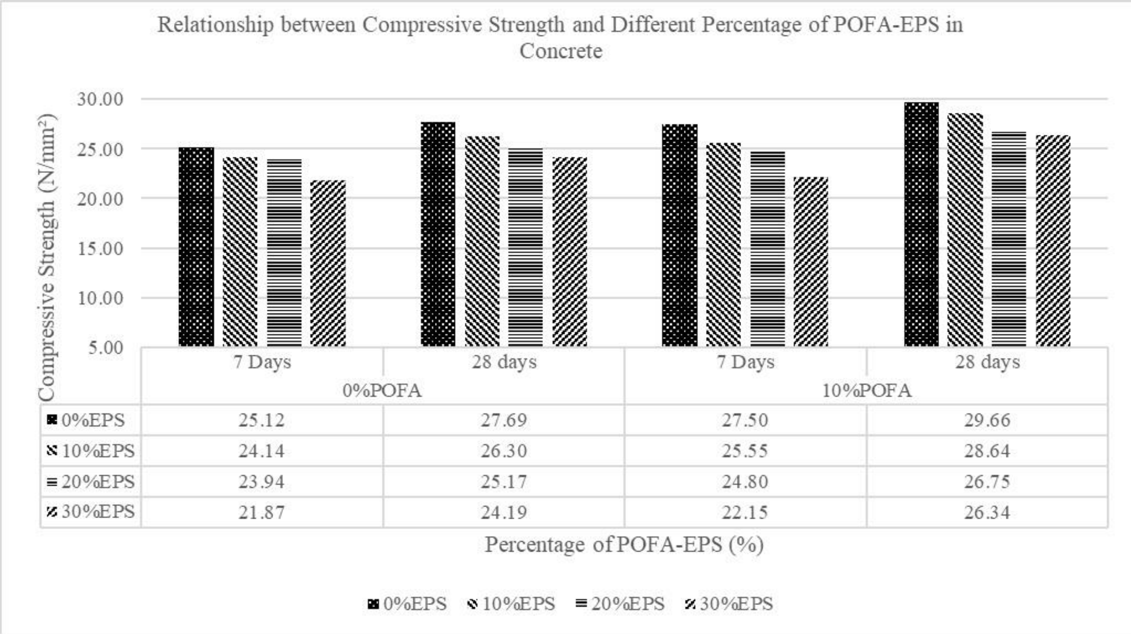

Figure 9. Compressive strength of concrete containing EPS and POFA

contributed to this phenomenon, leading to higher concrete strength. The smaller particle size of the POFA enables it to fill the micro-voids between cement particles, as mentioned in the works of Kwek (2022) [20] and Isaia *et al.* (2003) [21]. This micro-filling capability, with a small amount of POFA used in this study, is the primary factor responsible for the increased compressive strength of the concrete. Aside from that, POFA is a highly reactive pozzolanic material. When it reacts with calcium hydroxide ($Ca(OH)_2$), it forms additional calcium silicate hydrate (C-S-H) gel. This C-S-H gel fills the voids between cement particles and aggregates, resulting in a denser microstructure. The densification leads to improved bonding between cementitious materials, enhancing overall strength.

However, the compressive strength of concrete cubes containing 10% POFA with 10% EPS, 20% EPS, and 30% EPS followed the decreasing trend observed earlier.

3.3. Pull-out Performance of EPS-POFA Concrete

As mentioned above, Pull-out tests were conducted for each sample to obtain the maximum load before failure occurs to the concrete mix. The pull-out force in this study seems to represent the bonding performance between concrete and steel. It is carried to each sample by applying a tensile load to the samples inserted in the rig mould in the UTM. The load is gradually increased until failure occurs in each sample.

Figure 10 shows the pull-out force of the concrete samples with 0% POFA and 10% POFA replacement with 0% to 30% EPS. After 7 days and 28 days, the pull-out force of the normal concrete was 47.02 kN and 53.24 kN, respectively. Similar trend with compressive strength: the pull-out force decreases as the replacement ratio of EPS increases due to EPS failure to effectively interact with cement, resulting in a weak bond, and it also exhibits low bonding strength between steel and concrete [1]. However, in this study, POFA is introduced as an addition to enhance the bond strength between EPS-containing concrete and steel. As shown in Figure 10, concrete with 10% POFA may increase pull-out force compared to normal concrete. In this study, 10% POFA appears to improve the bond between EPS beads and cement and then improve the pull-out force. As known, due to the pozzolanic properties of 10% POFA, it can react with lime or $Ca(OH)_2$ from the cement hydration process to form additional (C-S-H) with binding properties that are known to enhance the concrete pull-out force. The same result was also found by Ranjbar *et al.* (2016) [22], who stated that the 10% POFA in concrete gave better performance compared to normal concrete.

4. CONCLUSION

In conclusion, this research aimed to examine the bonding behavior of concrete containing EPS and POFA, utilizing laboratory tests as the investigative method. The findings shed light on the influence of EPS content in the concrete mix on its compressive strength and pull-out force capacity. It was observed that a higher proportion of EPS led to a reduction in both the compressive strength and pull-out force of the concrete. However, the study also revealed the positive effects of incorporating 10% POFA in the concrete mixture. This addition enhanced the bond between EPS beads and the cement matrix, as well as the bond between concrete and steel reinforcement. Remarkably, the concrete's compressive strength and bonding force, when supplemented with 10% POFA, surpassed that of the conventional concrete strength. As a result, the inclusion of 10% POFA in the concrete mix presents several advantageous outcomes. It has the potential to elevate the overall strength and pull-out force of the concrete, making it a promising approach for enhancing the performance of concrete containing EPS and contributing to the development of sustainable and high-performing construction materials. Further research and exploration in this direction may pave the way for more effective

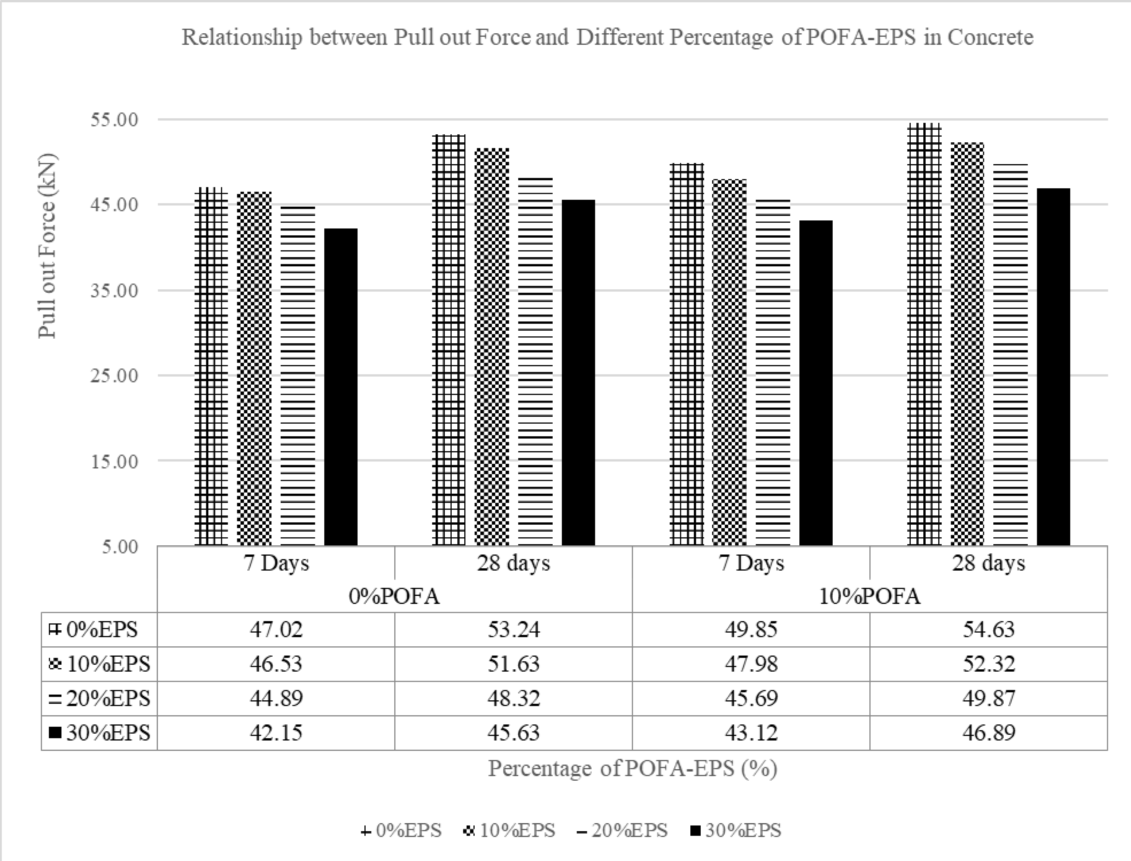

Figure 10. Pull-out force of concrete containing EPS and POFA

utilization of both EPS and POFA in concrete applications, ultimately benefiting the construction industry with environmentally friendly and resilient building materials.

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