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Influence of styrofoam-based additives on the mechanical properties of mortar for concrete roof tile production

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ABSTRACT

Concrete roof tile are widely used as roofing material due to its durability and performance. However, concrete roof tiles have relatively high weight and their production cost limit broader application. This study aims to develop an environmentally friendly lightweight concrete roof tile by adding styrofoam waste as a partial substitute for fine aggregates in the mortar mix. Four percentage variations of styrofoam content were used in making mortar and roof tile samples, which are 0%, 4%, 8%, and 12% relative to the total volume of sample. These variations were chosen to investigate the effect of styrofoam addition on the mechanical and physical properties of mortar and concrete roof tiles. A series of tests were also conducted, such as compressive, tensile, and flexural strength tests of mortar, flexural strength of roof tiles, as well as impermeability and porosity tests of the final products. The results of these tests indicate that the optimal mechanical performance was achieved at 8% styrofoam content, with mortar flexural strength reaching 5.05 MPa and roof tile flexural strength at 4.58 MPa. Although compressive strength declined with increasing styrofoam content, values remained within acceptable limits for non-structural applications. All roof tile samples met the impermeability criteria based on SNI 0096:2007, which states that there must not be water seepage through the samples for approximately 20 hours ± 5 minutes, regardless of their styrofoam content. Finally, it can be concluded that styrofoam can be effectively repurposed as an additive in concrete roof tile production, resulting in a lightweight, cost-effective, and sustainable building material.

Keywords: styrofoam, concrete roof tile, mortar, mechanical property, physical property, porosity, permeability

1 Introduction

Concrete roof tile is a non-structural building material made from a mixture of Portland cement, fine aggregates, water, and lime, with the potential inclusion of other additional additives. These tiles are relatively heavy with an average weight of approximately 4.4 kg per unit, which poses a challenge as the weight of the roofing material affects the dimensions and structural requirements of the buildings. Moreover, one of the main drawbacks of concrete is its brittle nature, its limited tensile strength, and its relatively high weight. Improving concrete roof performance in terms of compressive, tensile, and flexural strength is necessary. However, such an effort has to be accompanied with attempts to reduce the density of concrete roof.

One approach to address concrete roof tile weight issue is to incorporate other ingredients into the mixture, such as aluminum fibers. The addition of 0.04% fibers into the mix is proven to increase compressive strength of the concrete [1]. Other than aluminum fibers, previous studies also suggest that styrofoam can also be added into the mortar mix for concrete. Styrofoam, a type of polystyrene, has been widely used in various applications including packaging materials for electronic and various other products. As a non-biodegradable material, styrofoam is designed for single use but may take hundreds of years to decompose in landfills or natural environments. Hence, it is necessary to reuse and repurpose styrofoam waste to reduce environmental

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pollution and support sustainable construction practices [2], [3].

In general, incorporating expanded polystyrene in concrete construction can reduce production cost, improve thermal insulation, and reduce the dead load of the building [4]. Similar studies have been performed in the past to observe the effects of styrofoam addition into concrete mortar mix. In these previous studies, styrofoam waste was utilized as an alternative filler material of mortar mixture of cement block as well as added into concrete tile material together with coco peat fiber [5], [6]. A previous study of styrofoam and polypropylene fibers into foamed concrete also proven to enhance its mechanical performance [7]. However, the suitability of styrofoam or styrofoam-based additives in concrete roof tile have not been extensively studied.

The main purpose of this study is to develop a lightweight and environmentally friendly concrete roof tile by adding styrofoam waste into the mortar mix. This study investigates the effect of various styrofoam content levels (0%, 4%, 8%, and 12% by volume) on the mechanical and physical properties, such as compressive, tensile, and flexural strength of the mortar, as well as impermeability and water absorption of the concrete tiles. Additionally, this study also compares the surface appearance of conventional concrete roof tiles with the ones containing styrofoam. The outcomes of this study are expected to contribute to sustainable construction practices by repurposing styrofoam waste while also reducing the use of conventional aggregates. The resulting concrete roof tiles have to comply with the mechanical standards outlined in [8].

2 Data and Methods

This research was using Portland cement, fine aggregate (sand), clean water, and styrofoam waste as the primary components of the mortar mix for concrete roof tiles. The styrofoam was sourced from electronic packaging waste after it was shredded into small particles before mixing. Four mortar mix variations were prepared by replacing a portion of the fine aggregate with styrofoam at different percentages, which are 0% as control, 4%, 8%, and 12% by volume, following the method of [9]. The base mix ratio for mortar was set at 1:2 for cement and sand with a water-to-cement ratio of approximately 0.7, adjusted based on workability. Tables 1 to 3 specify the exact weights of each component used in cube mortar, briquette mortar, and roof tile production, respectively. The complete composition of cube and briquette-shaped mortar samples as well as concrete roof tile samples are contained in **Table 1-3**.

Mortar samples were then mixed manually and cast into molds. There are two types of samples were produced during this study, namely cube (**Figure 1**) and briquette-shaped samples. The cube samples were made for compressive strength testing, while the briquette-shaped samples were made for tensile and flexural strength testing. These two types of samples were demolded 24 hours after casting and cured in water for 3 days to ensure proper hydration and strength development. On the other hand, roof tiles samples were cast by using a mold of 30 × 30 × 1.5 cm size. The curing period was limited to 3 days to represent early-age strength behavior and to simulate practical production conditions of concrete roof tiles, which typically undergo short curing durations before use. The average weight of the roof tiles was approximately 3.6 kg for the control sample. The mixture of concrete roof tile sample was placed into the mold and compacted by utilizing a mechanical press. The tiles were then demolded and cured through water immersion for 3 days, followed by air drying for 4 days.

Table 1. Composition calculation for cube mortar production

%	Cement (gram)	Sand (gram)	Water (gram)	Loss Factor	Styrofoam (gram)
0	584.94	1179.83	409.46	1.25	-
4	561.54	1132.64	409.46	1.25	30
8	538.14	1085.45	409.46	1.25	60
12	514.74	1038.25	409.46	1.25	90

Table 2. Composition calculation for briquette-shaped mortar production

%	Cement (gram)	Sand (gram)	Water (gram)	Loss Factor	Styrofoam (gram)
0	359.38	724.89	251.57	1.25	-
4	345.01	695.89	251.57	1.25	18.43
8	330.63	666.90	251.57	1.25	36.84
12	316.26	637.90	251.57	1.25	55.29

Table 3. Composition calculation for concrete roof tile production

%	Cement (gram)	Sand (gram)	Water (gram)	Loss Factor	Styrofoam (gram)
0	14,782.50	40,520.25	10,347.75	1.25	-
4	14,191.20	38,899.44	10,347.75	1.25	648
8	13,599.90	37,278.63	10,347.75	1.25	1296
12	13,008.60	35,657.82	10,347.75	1.25	1944

Figure 1. Cubic-shaped mortar samples after curing process.

After getting all the samples ready, several mechanical and physical test were conducted, such as compressive, tensile, and flexural strength tests as well as impermeability and porosity tests. The compressive strength testing was performed on 5 mortar cubes aged 7 days using a standard compression testing machine, following [10] as seen in **Figure 2**, while axial tensile strength of 5 briquette samples was tested using the method contained in [11]. Flexural strength, on the other hand, was evaluated for both 5 mortar samples and 5 concrete roof tile samples (**Figure 3**). For roof tiles samples, testing followed the [8] guideline, by using a two-point load system with a 26 cm span and incremental loading measured using a proving ring.

Figure 2. Compressive strength test for mortar samples.

Figure 3. Flexural strength test for concrete roof tile samples.

The objective of impermeability test is to assess the resistance of roof tiles to water seepage. This test was performed by using a circular acrylic mold (9 cm in diameter with the height of 5 cm) that was sealed onto the surface of the roof tile by utilizing sealant, glue, and cement paste. Water was then added to a depth of 1.5 cm, and any seepage through the tile was observed over 15 to 25 hours period in an indoor environment to avoid evaporation. The porosity test was conducted by oven-drying roof tiles to a constant weight, then immersing them in water for 24 hours. After immersion, the surface of the roof tiles were wiped with a damp cloth and the sample was weighed again to calculate water absorption.

The data obtained from the aforementioned tests included the average compressive strength, tensile strength, and flexural strength for mortar, as well as the flexural strength, impermeability, and porosity for roof tiles. Results were analyzed to determine the optimal styrofoam content that balances lightweight properties of roof tile with its mechanical performance as well as its durability in accordance to [8].

3 Results & Discussion

3.1 Compressive Strength of Mortar

Compressive strength tests were performed on 5 mortar cube samples for each variation of styrofoam content (0%, 4%, 8%, and 12%) after aging them as long as 7 days. The highest compressive strength was found for the control sample with 0% styrofoam content at 21.68 MPa. Our compressive strength results also show that as styrofoam content increased, compressive strength decreased significantly. Mortars with 4%, 8%, and 12% styrofoam content show average compressive strengths of 16.32 MPa, 13.52 MPa, and 12.16 MPa, respectively. This trend indicates the lightweight and non-structural characteristics of styrofoam, which has the ability to replace denser sand particles and leads to reduced load-bearing capacity [12] [13]. However, it is important to note that compressive strength remained within an acceptable range for certain non-load-bearing applications even with 4% styrofoam content. The complete results of compressive strength tests of mortar are contained in **Table 4.**

Table 4. Compressive Strength Test Results of Mortar

%	Compressive Strength (MPa)					Mean (MPa)
	1	2	3	4	5	
0	22.00	21.60	22.40	22.00	20.40	21.68
4	18.00	14.80	15.60	16.00	17.20	16.32
8	10.40	16.00	15.20	14.40	11.60	13.52
12	13.20	11.60	10.80	12.40	12.80	12.16

3.2 Axial Tensile Strength of Mortar

The results of axial tensile strength test shown in **Table 5** were slightly more variable compared to the previous compressive strength test. The addition of 8% styrofoam into the mortar mix shows an increase in tensile strength, which most likely be caused by improved internal bonding of microvoids and increased material elasticity of the mortar. However, more addition of styrofoam does not cause a continuous increase in axial tensile strength as shown by the results of specimen with 12% styrofoam content. Our results show a similar trend to [14] where tensile strength improved as styrofoam content is increased only to decline significantly if styrofoam content keep being added. This is likely due to weakened bonding and dominance of low-strength styrofoam particles in the mortar matrix.

Table 5. Axial Tensile Strength Test Results of Mortar

%	Axial Tensile Strength (MPa)					Mean (MPa)
	1	2	3	4	5	
0	1.59	1.18	1.20	1.58	1.19	1.35
4	0.95	2.15	1.25	0.92	2.04	1.46
8	1.96	1.55	1.55	1.46	1.32	1.54
12	0.82	0.86	0.86	0.91	1.09	0.87

3.3 Flexural Strength of Mortar

Table 6 contains flexural strength test results of mortar. These results show that higher styrofoam content decreases flexural strength of a mortar, while the control mix with 0% styrofoam content has the highest flexural content. The decrease of flexural strength was more gradual compared to that of compressive strength, indicating that styrofoam addition may reduce stiffness and load resistance capacity under bending. Although both compressive and flexural strengths decreased with reduced density as styrofoam content is increased, the decline in flexural strength was noticeably slower compared to compressive strength [15].

Table 6. Flexural Strength Test Results of Mortar

%	Flexural Strength (MPa)					Mean (MPa)
	1	2	3	4	5	
0	4.53	5.91	5.01	5.32	4.50	5.05
4	4.50	4.50	4.36	4.64	4.08	4.42
8	4.19	4.16	4.08	3.91	4.22	4.11
12	3.40	4.36	3.88	4.28	4.08	4.00

3.4 Flexural Strength of Concrete Roof Tiles

The flexural strength of concrete roof tile samples was tested by using a two-point loading setup with the results displayed in **Table 7**. There results were notably different compared to those of mortar samples, showing that addition of 8% styrofoam content resulting in optimum flexural strength (4.58 MPa), higher than the control sample. This improved performance may be caused by the redistribution of stress and energy absorption from the lightweight particles of styrofoam inside the roof tile [16], [17]. However, flexural strength decreased at 12% styrofoam content.

3.5 Impermeability and Porosity of Concrete Roof Tiles

The impermeability test results (**Table 8**) show that there is no water seepage for all roof tile samples regardless of its styrofoam content. This agrees with SNI 0096:2007 [8], which states that there must not be water seepage through the samples for approximately 20 hours $\pm$ 5 minutes. This indicates that styrofoam addition did not compromise the consistency of concrete roof tile matrix.

On the other hand, porosity test of the concrete roof tile samples shows optimum result at 7.87 MPa, correlating with lower water absorption. An increase in styrofoam content tends to increase micro voids, which may increase water absorption if not carefully controlled. However, hydrophobic characteristic may also partially mitigate this effect [18].

Table 7. Flexural Strength Test Results of Roof Tiles

%	Flexural Strength (MPa)					Mean (MPa)
	1	2	3	4	5	
0	2.90	4.36	2.48	3.67	4.25	3.53
4	4.63	4.66	4.02	2.99	4.94	4.25
8	5.10	4.45	3.38	5.87	4.11	4.58
12	4.20	3.78	4.23	3.85	4.08	4.03

Table 8. Impermeability Test Results of Roof Tiles

%	Seepage	%	Seepage
0	No	8	No
0	No	8	No
0	No	8	No
0	No	8	No
0	No	8	No
4	No	12	No
4	No	12	No
4	No	12	No
4	No	12	No
4	No	12	No

The experimental results elaborated in the last section of this paper revealed that styrofoam addition as a partial substitute of fine aggregates in mortar significantly affected the mechanical properties of both mortar and concrete roof tile samples. The discussion interprets these results based on different styrofoam content by volume (0%, 4%, 8%, and 12%) to determine the optimum addition supporting lightweight and durable concrete roof tile performance.

Compressive stress of mortar decreased as styrofoam content increased (**Figure 4**), with the peak compressive strength of 21.68 MPa at 0% styrofoam addition. This decrease of compressive stress as Styrofoam content is increased may be related to the lack of binding capability of Styrofoam. The lightweight and low-density characteristics of Styrofoam are not likely contributing to increase compressive strength, instead added Styrofoam particles have the capability to replace denser cement block particles significantly. This in turn will increase voids of the concrete and lowering its density as well as cohesion [6].

Meanwhile, tensile strength of mortar tends to fluctuate and shows a notable improvement at 8% of styrofoam addition, reaching 1.54 MPa before decreasing at 12% of styrofoam addition as shown in **Figure 5.** This suggests that at certain levels, Styrofoam particles may effectively help distributing tensile stress within the concrete due to its slightly flexible characteristics. However, higher percentage (12%) Styrofoam addition lowers tensile strength into 0.866 MPa, which most likely due to weaker cohesion between mortar particle. This finding is similar to [5], where concrete with Styrofoam addition maintains structural integrity up to a particular threshold.

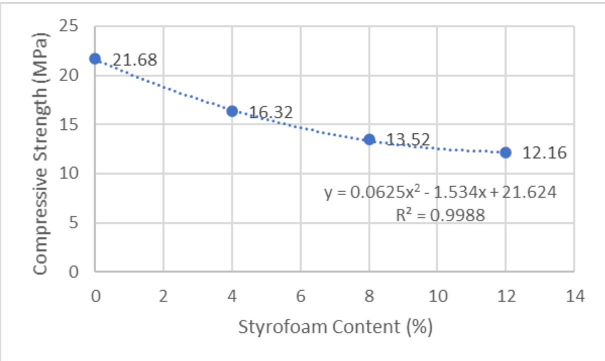

Figure 4. Relationship of styrofoam content and compressive strength of mortar.

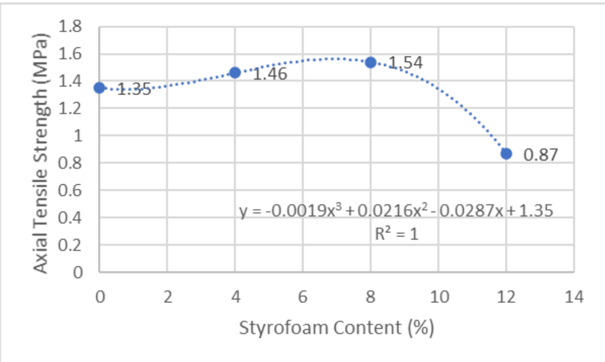

Figure 5. Relationship of styrofoam content and axial tensile strength of mortar.

Flexural strength of a mortar also decrease as styrofoam addition is increased with the highest value reaching 5.05 MPa at 0% styrofoam addition as shown in **Figure 6**. On the contrary, flexural strength of roof tile improve with moderate addition of styrofoam content of 8%, resulting in flexural strength of 4.58 MPa (**Figure 7**). This indicates that the inclusion of lightweight material such as styrofoam may increase the ability of roof tile in resisting bending forces. Similar results were also observed by [19], where the addition of lightweight materials initially increased flexural strength up to certain level but later decreased it as the percentage was increased.

All roof tile samples regardless of the styrofoam content have met the impermeability requirement specified in [8], since they showed no water seepage during the impermeability testing. This indicates that Styrofoam particles may enhance waterproof performance of concrete due to its hydrophobic characteristics, preventing water penetration as well as providing resistance against seepage.

Porosity also remained within acceptable levels of 7.87%, with no significant compromise in water absorption capacity. Even though the addition of Styrofoam increases micro voids in the concrete, these voids remain within acceptable limit. On the other hand, adding lightweight material into the concrete mix is proven to increase porosity with manageable quality thresholds [20].

The results of study suggest that incorporating up to 8% styrofoam addition provides an optimal balance between mechanical performance and weight reduction of concrete roof tile. Aside from its engineering benefit, styrofoam addition into concrete roof tile production will also benefit the environment through waste reduction. Therefore, styrofoam can be repurposed and effectively utilized in the production of environmentally friendly and lightweight concrete roof tiles without sacrificing essential functional properties [21].

Despite these findings, this study has several limitations. The mechanical properties were evaluated at early ages, and long-term performance such as 28-day strength and durability under environmental exposure were not investigated. In addition, microstructural analysis such as SEM was not conducted to directly observe ITZ characteristics. Future studies are recommended to address these aspects and further optimize styrofoam particle size and distribution.

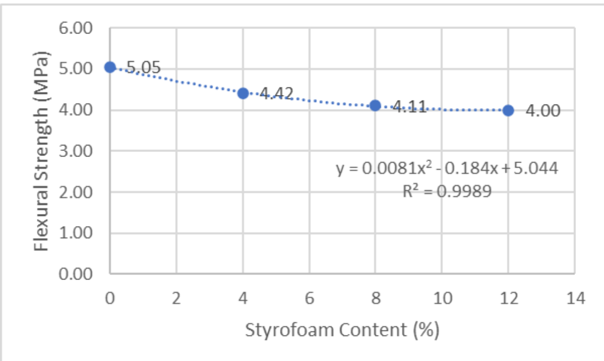

Figure 6. Relationship of styrofoam content and flexural strength of mortar.

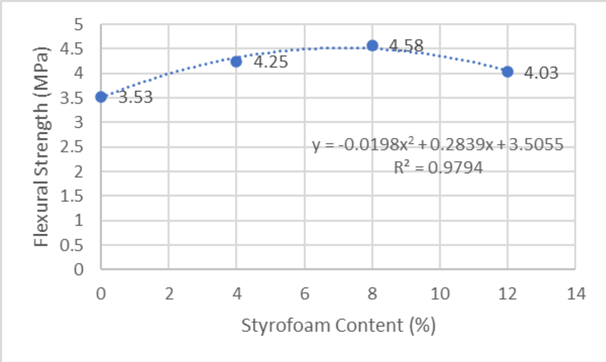

Figure 7. Relationship of styrofoam content and flexural strength of concrete roof tile.

4 Conclusion

An environmentally friendly and lightweight concrete roof tile has been developed by adding styrofoam waste as a partial substitute for fine aggregates with the styrofoam content of 0%, 4%, 8%, and 12%. The styrofoam content variations were set to investigate the effect of styrofoam addition on the mechanical and physical properties of mortar and concrete roof tiles. Some tests were conducted to clarify the mentioned properties namely compressive, tensile, and flexural strength tests of mortar, flexural strength of roof tiles, as well as impermeability and porosity tests of the final products. The results of these tests leads to the following findings.

- Compressive strength decreased along with higher addition of styrofoam content.
- Tensile strength showed a peak at 8% styrofoam content, indicating optimal performance at moderate styrofoam addition.
- Flexural strength of both mortar and roof tiles was highest at 8% addition of styrofoam content.
- All tiles passed impermeability standards and porosity also remained within acceptable levels regardless the addition of styrofoam content.
- Overall, 8% styrofoam addition is the optimal content in terms of balancing mechanical strength and lightweight performance.

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