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Influence of Fine Aggregate Ratios on the Performance of Lightweight Polyurethane Concrete from EMC Waste

Muhamad Afnan Hasri[1], Mohd Sufyan Abdullah[1]*, Hasnida Harun[1], Hilmi Kosnin[1]

[1] *Department of Civil Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA*

*Corresponding Author: sufyan@uthm.edu.my
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Abstract

The rapid generation of electronic waste (e-waste) has become a significant environmental concern, necessitating innovative recycling strategies in the construction industry. The objective of this research is to investigate the possibility of recycling silicon dioxide SiO_2 from Epoxy Molding Compound (EMC) waste to serve as a sustainable filler for Lightweight Polyurethane Concrete (LWPC). In this study, SiO_2 was derived from EMC waste through a thermal decomposition (pyrolysis) process at an isothermal temperature of 500°C for 5 minutes and subsequently sieved to a particle size of 425 µm to ensure optimal micro-filling capability. The experimental program was designed to partially substitute 5% of Ordinary Portland Cement (OPC) with the reclaimed EMC silica and an additional 5% of Silica Fume across three different sand-to-cement ratios, specifically 2.5%, 3.0%, and 3.5%. The physical, mechanical, and thermal properties of the composites were rigorously examined following a 28-day air-curing period. The findings revealed that all EMC-modified mixes yielded densities of less than 1920 kg/m^3, successfully identifying them as structural lightweight concrete according to ASTM C567 standards. Among the tested proportions, mix 2 (Ratio 3.0) was found to be the optimal composition, achieving a compressive strength of 1.34 MPa, which outperformed the control sample's 1.30 MPa due to the effective micro-filling action and pozzolanic reactivity of the EMC particles. Furthermore, the introduction of EMC particles refined the pore structure, reducing water absorption to 22.72% and enhancing thermal insulation performance. Mix 2 achieved a thermal conductivity value of 0.423 W/mK, representing an 8.4% improvement in insulation compared to the control sample. These results demonstrate that recycled EMC waste is a viable alternative supplementary cementitious material for non-structural applications, such as partition walls, contributing to a circular economy and a sustainable building environment

1. Introduction

As a result of rapid advances in technology along with the shortened life cycle of electronic products, handling electronic waste (e-waste) has become an environmental problem worldwide. EMC waste is one of the difficult-to-deal-with fractions because it is made from thermosetting materials which are commonly used for packaging in semiconductor industry [1]. EMC waste is produced in significant quantities on an annual basis and the majority of which will be disposed of in landfill sites causing soil contamination and loss of precious organics resources present in the matrix such as Silica [2]. To tackle this problem, new recycling techniques are needed to remove and reclaim these components from the waste stream to help reduce the environmental impact of the electronic industry.

At the same time, construction sector is increasingly required to embrace sustainable practices and minimize its dependence on traditional material inputs such as Ordinary Portland cement (OPC), which is known for being energy consumed with high carbon dioxide emissions [3]. Lightweight concrete is an attractive option for contemporary constructions to lessen the structural deadloads and provide relatively good thermal insulating performance. With recycled silicon dioxide (SiO_2) from EMC waste as a pozzolanic material or micro-filler, high performance Light Weight Polyurethane Concrete LWPC can also be produced [4]. This practice offers an alternative route for hazardous e-waste disposal, whilst also aiding the release of greener construction materials in response to demand from a circular economy.

1.1 Problem Statement

Although the waste from Epoxy Molding Compound (EMC) has potential sources as the silicon dioxide (SiO_2), it has not been widely used in construction industry because of difficulties involved in recycling an active silica from cured resin matrix. The raw waste of EMC for instance, generally is an inactive material that would be thermally treated by a proper temperature such as pyrolysis to break off the organic matter and provide silica particles enough reticular space to have strong bounding. At present, the detailed studies on recycled particles mixed into polyurethane-based concrete matrixes plus the combination of other pozzolans such as Silica Fume are rather limited. Without appropriate processing and mix design techniques, waste fillers can result in heterogeneous material performance and fail to be widely adopted.

Furthermore, the balance between achieving a lightweight structure and maintaining sufficient mechanical strength presents an important technical. The proportion of fine aggregates (sand) plays a necessary role to determine the density, water absorption, compressive strength, and thermal conductivity of the concrete, yet the specific influence of varying sand-to-cement ratios in the presence of EMC fillers is not fully understood. If the aggregate ratio is not optimized, the resulting concrete may affect from high water absorption or insufficient load-bearing capacity. However, this research is essential to determine the optimal fine aggregate ratio that maximizes the performance of LWPC containing recycled EMC waste and ensures it meets the standards for structural or non-structural applications.

2. Methodology

2.1 SiO_2 Extraction Method

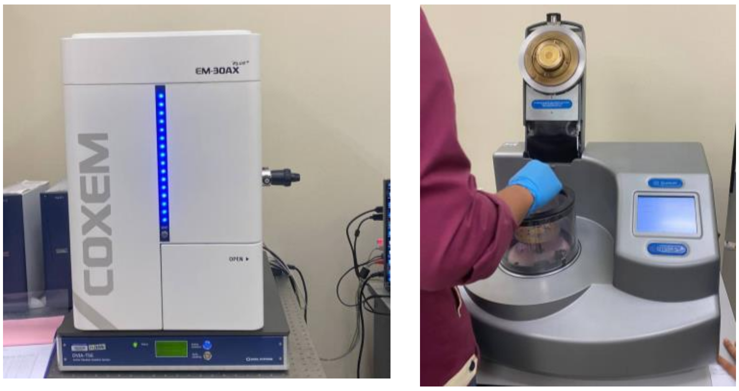
The EMC wasted were obtained from ST Microelectronics Sdn. Bhd. in Muar, Johor, Malaysia. The waste was mechanically crushed and sieved to reach the 425 μm particle size [5]. The EMC was in thermal decomposition (pyrolysis) treatment in a Protherm Muffle Furnace at an isothermal temperature of 500°C for 5 minutes was carried out to burn off the organic resin matrix and separate silica inorganic phase [6]. The char produced was gathered as a partial replacement of cement.

2.2 Characterization of SiO_2

The morphological structure and elemental composition of the extracted silica were analyzed by using Scanning Electron Microscopy (SEM) integrated with Energy-Dispersive X-ray Spectroscopy (EDX) using a COXEM EM30AX instrument. Prior to imaging, sample preparation was critical due to the non-conductive nature of both the raw EMC waste and the recovered silica residue. Small quantities of the powder samples were mounted onto aluminum stubs using double-sided conductive carbon tape [7]. To mitigate charging effects caused by the electron beam and to ensure high-resolution imaging, the sample surfaces were coated with a thin layer of gold using a Sputter Coater for approximately 60 seconds.

After the coating process, the samples were examined in the SEM vacuum chamber at an accelerating voltage of 20 kV. The pristine, organic-rich raw EMC and the pyrolyzed residue could also be compared directly by examination of this image, which revealed exposure of the silica fillers and degradation of the epoxy resin matrix. Purity of recovered material was also confirmed quantitatively by EDX at the same time. The analysis showed a change in the elemental composition, where a decrease in carbon (C) and an increase in silicon (Si) and oxygen (O) content was confirmed e.g., after heat treatment.

Progress in Engineering Application and Technology Vol. 7 No. 1 (2026) p. 111-117



(a) (b)

Fig. 1 ***(a)*** *COXEM SEM-EDX (EM30AX)* ***(b)*** *Sputter Coater*

2.3 Mix Design

The mixed compositions adopted in this investigation are provided. For comparison purpose, a control specimen is cast by 100% Ordinary Portland Cement (OPC) with 3.0% sand-to-cement ratio as a performance reference. With the replacement of 5% EMC and 5% SF by mass cement for all modified mixes which is mix 1 (2.5%), mix 2 (3.0%), and mix 3 (3.5%), and can be checked for their potential ability as supplementary cementitious materials. The binder system utilized a two-component polyurethane (PU) resin comprising Polyol and Isocyanate. These components were mixed at a fixed weight ratio of 1:1 to form the polyurethane matrix.

Table 1 Mix Ratio of LWPC

Sample	Cement (g)	EMC (g)	Silica Fume (g)	Fine Aggregate (g)	PU Resin (A+B) (g)	Hardener (g)	Water (g)
Control	694.6	0	34.73	2083.8	1041.9	20.83	416.76
Mix 1 (2.5%)	661.5	33.1	33.1	1653.75	992.3	19.8	396.9
Mix 2 (3.0%)	661.5	33.1	33.1	1984.5	992.3	19.8	396.9
Mix 3 (3.5%)	661.5	33.1	33.1	2315.3	992.4	19.8	396.9

2.3.1 Sample Preparation

First, all the dry mixed cement, fine aggregates, EMC and silica fume were mixed in a mechanical mixer to obtain uniform mixture. The dry mix was then mixed with water to prepare a slurry made of mortar. At the same time, a liquid binder composition was formed in another container by mixing the Polyol and Isocyanate components. The resin blend was agitated while the chemical foaming reaction began, and the prepared mass was poured immediately into a concrete slurry and stirred violently to cause homogeneous distribution of the binding agent in the matrix.

Upon achieving a consistent mixture, the fresh concrete was cast into 100 mm × 100 mm × 100 mm steel cube moulds. Due to the expansive nature of the polyurethane reaction, the moulds were filled to approximately 80% of their capacity to prevent overflow while ensuring sufficient compaction. Thus, an entrapped air void is removed with a tamping rod during casting. After the mixture had expanded and cured, the remaining excess foam at the top was trimmed so that it laid flat. The specimens were then demoulded and placed in a controlled environment for air curing for 28 days at an ambient temperature of 27 ± 2°C and a relative humidity of 60 ± 5% prior to testing [8].

3. Results and Discussion

3.1 Scanning Electron Microscopy (SEM) Energy-Dispersive X-ray Spectroscopy (EDX)

Figure 2 shows an SEM micrograph of the EMC waste that was collected after the pyrolysis process. The picture shows a rough and porous shape, which means that the heat has broken down the organic epoxy resin matrix. This structural breakdown clearly shows the different inorganic silica fillers, which make the surface rough and helps the cementitious matrix lock together mechanically.

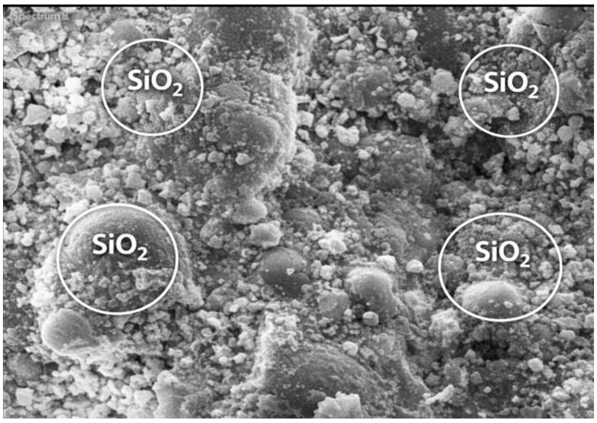


Fig. 2 *SEM micrograph showing the morphology of EMC waste particles after the pyrolysis process*

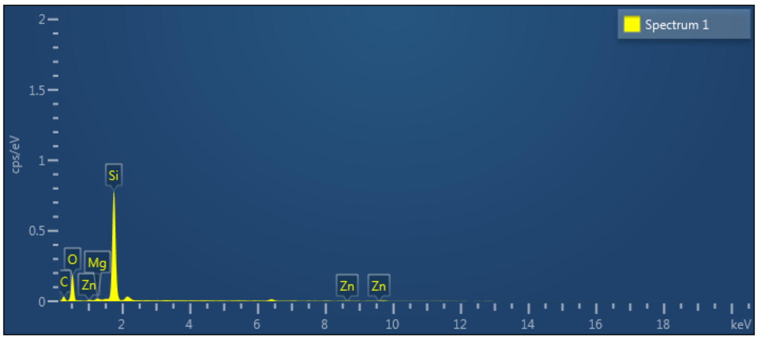


Fig. 3 *Elemental composition of extracted SiO_2*

The EDX elemental given in Figure 3 shows that the recovered residue is mainly made of Oxygen (41.57 wt%) and Silicon (28.20 wt%). The sum of 69.77% emphasizes the dominance of Silicon Dioxide SiO_2 in terms of mass percentage, endorsing indeed the silica filler present in major EMC formulations. The carbon present (26.78%) is due to the Carbonaceous char, residual from the pyrolysis of Epoxy resin binder. Some trace elements such as Mg, Zn were also detected and probably originated from secondary additives. The overall of these findings is that those residues subjected to the pyrolysis step at 600 °C were successfully cleaned from the organic binder, resulting in a silica-rich material potentially appropriate for cementitious composite use [9].

3.2 Density

The density of concrete is an important physical property which considerably influences the classification of structural members as well as reduces the dead load where such a reduction is essential. The density of the LWPC with EMC silica was also determined in this work after 28 days of curing. The outcome was compared with the provisions of ASTM C567, which restricts a maximum density for structural lightweight concrete of 1920 kg/m3[10].

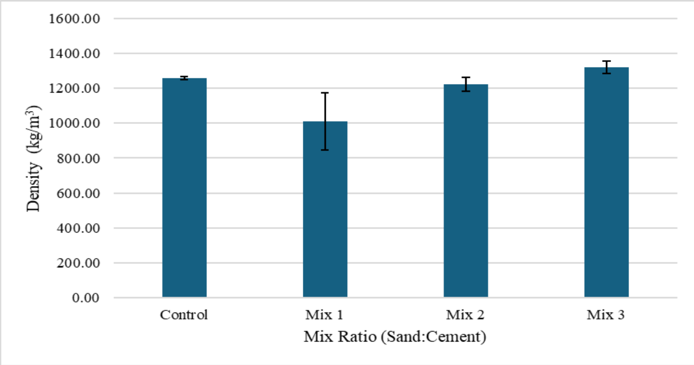


Fig. 4 *Density Result for 28 Days at Difference Mixture*

The range of densities from lowest of 1010.00kg/m^3 for mixed 1 to highest 1320.00 kg/m^3 for mix 3 was obtained. The relationship between the density and sand-to-cement ratio from 2.5% to 3.5% was approximately linear. This behavior is due to the higher specific Gravity of silica sand when compared with the polyurethane foam matrix. Therefore, an increase in fine aggregate proportion leads to a denser configuration of composite. Mix 1 (Ratio 2.5%) was deduced as the best recipe for minimizing weight reduction.

Furthermore, the inclusion of EMC waste contributed to a reduction in density. When comparing specimens with a constant sand-to-cement ratio of 3.0, mix 2 recorded a lower density is 1223.33 kg/m^3 than the Control sample is 1258.33 kg/m^3. This reduction suggests that the pyrolyzed EMC particles possess a lower specific gravity than Ordinary Portland Cement (OPC). Overall, all formulated mixes successfully met the criteria for lightweight concrete classification, demonstrating that the material's density can be tailored by adjusting aggregate ratios while maintaining its lightweight characteristics.

3.3 Water Absorption

Water absorption is an important factor indicating porosity and durability in concrete, especially for lightweight concrete as internal pore's structure governs the mechanical strength. High water absorption rates are commonly linked to high permeability, resulting in lower resistance toward the effects of extreme weather. In the present study, absorption of water by Lightweight Polyurethane Concrete (LWPC) was studied in which silicon dioxide SiO2 from Epoxy Molding Compound (EMC) waste is used as partial replacement for cement. The study focuses on the effects of adding EMC derived silica (as a micro-filler) for pore refinement and microstructural densification. Figure 5 shows the water absorption of cube specimens was reported in the next section following 28 days of curing to indicate how different fine aggregate ratios would affect the overall impermeability of the composite.

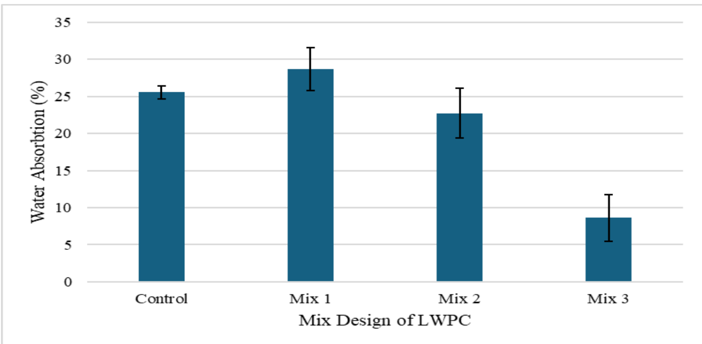


Fig. 5 *Water Absorption Result for 28 Days at Difference Mixture*

The results demonstrate a clear negative correlation between fine aggregate proportion and concrete permeability which is higher sand content significantly improves moisture resistance. Mix 1 (ratio 2.5% ratio) exhibited the highest permeability, attributed to its low aggregate content which resulted in a porous and foam-dominated structure. Then, an increasing the aggregate loading in Mix 3 (3.5% ratio) densified the matrix and reduced interconnected voids, lowering water absorption to below 10%. Furthermore, Mix 2 demonstrated superior moisture resistance compared to the Control at the same dosage. This confirms the efficacy of ultra-fine EMC particles as micro-fillers, which refine the pore structure and obstruct capillary pathways present in the unmodified control mix.

3.4 Compressive Strength

Compressive strength is the most important mechanical property for the assessment of concrete structural behavior and load bearing capacity. It is an important measurable parameter for quality control and in the ability to withstand axial loads. In the present work, to investigate the possibility of using SiO2 recovered by Epoxy Molding Compound (EMC) waste as a partial replacement of cement, cube specimens were prepared. The study specifically aims to understand the effect of EMC addition mixed with different fine aggregate content (Mix 1, Mix 2 and Mix 3) on strength of Lightweight Polyurethane Concrete (LWPC). Figure 4.7 shows derived from 28 days of curing, which is indicative of the contribution of EMC silica to the mechanical properties in relation to control sample with polyurethane as matrix.

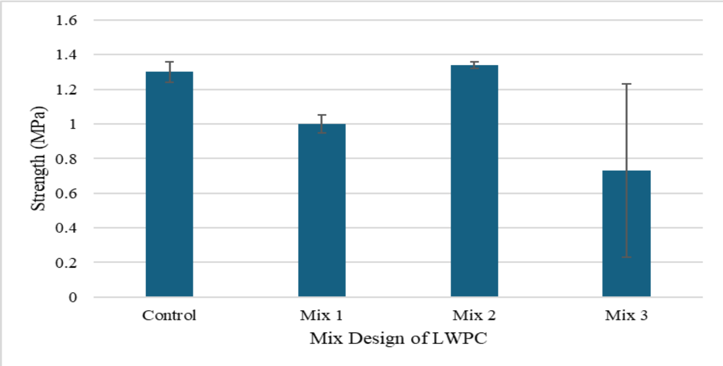


Fig. 6 *Compressive Strength Result for 28 Days at Difference Mixture*

The data shows a significant dependency on the sand-to-binder ratio. Mix 2 (Ratio 3.0%) achieved the optimal performance with the highest average compressive strength which is 1.34 MPa and this ratio will affect the result in reduced mechanical performance. Then, the mix 1 (Ratio 2.5%) shows a lower strength of 1.00 MPa. This reduction is attributed to a foam-dominated matrix with insufficient aggregate to form a stiff skeletal network, resulting in a porous and deformable structure. Lastly, mix 3 (Ratio 3.5%) exhibited the lowest strength at 0.73 MPa. This decline indicates that the sand loading exceeded the effective limit of the binder coverage. The high solid content in mix 3 led to poor workability and a dry mixture. It will prevent effective compaction and result in internal macro-voids. Therefore, a sand-to-binder ratio of 3.0% was identified as the critical threshold for mechanical stability in this study.

3.5 Thermal Conductivity

Thermal conductivity is the most important factor for assessing the insulation effect of building materials, which directly affects energy consumption and thermal comfort in buildings. Thermal Transmission Properties of the LWPC Samples The thermal transmission properties of the LWPC samples were calculated to investigate the effect of pulled silica and polyurethane binder system on heat transfer resistance. The products and results are assessed to verify the product as a thermal insulating, utilizing inherent low conduction of lightweight aggregates and porous systems. Polyurethane Concrete (LWPC) specimens were conducted in accordance with ASTM C518.

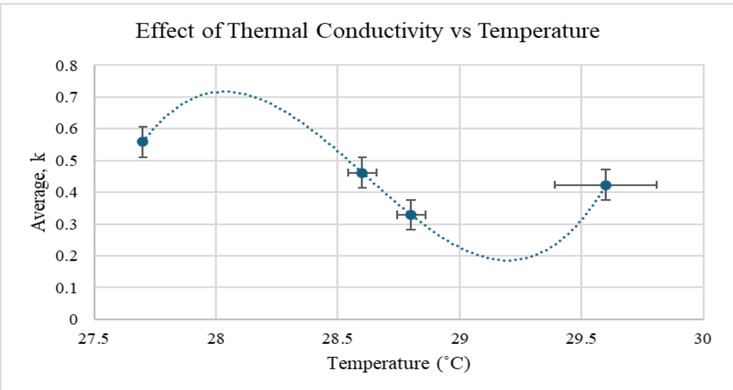


Fig. 7 *Thermal Conductivity Result for 28 Days at Difference Mixture*

The Lightweight Polyurethane concrete's thermal conductivity performance showed a direct linear relationship between the fine aggregate ratio and the thermal conductivity k-value. The thermal conductivity increased significantly as the silica sand content rose, ranging from 0.329 W/mK for mix 1 to 0.423 W/mK for mix 2, and finally reaching 0.559 W/mK for mix 3. This trend, on the other hand, is caused by crystalline silica sand replacing the insulating polyurethane foam matrix. Crystalline silica sand naturally has higher thermal conductivity. Mix 3 had more aggregate, which made solid pathways for heat to flow through. This reduced the number of air-filled voids that insulated space. Because mix 1 had less sand and more of the porous, air-filled foam structure that slows down heat flow, it was the best insulator.

4. Conclusions

The Lightweight Polyurethane concrete's thermal conductivity performance showed a direct linear relationship between the fine aggregate ratio and the thermal conductivity k-value. The thermal conductivity increased significantly as the silica sand content rose, ranging from 0.329 W/mK for mix 1 to 0.423 W/mK for mix 2, and finally reaching 0.559 W/mK for mix 3. This trend, on the other hand, is caused by crystalline silica sand replacing the insulating polyurethane foam matrix. Crystalline silica sand naturally has higher thermal conductivity. Mix 3 had more aggregate, which made solid pathways for heat to flow through. This reduced the number of air-filled voids that insulated space. Because mix 1 had less sand and more of the porous, air-filled foam structure that slows down heat flow, it was the best insulator.

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