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The Effects of Water to Cement Ratio on Polyurethane Concrete Towards SDG Goals

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Abstract

The growing demand for sustainable and lightweight construction materials has driven the development of innovative alternatives such as polyurethane lightweight concrete (PU-LWC). Compared to other lightweight concrete, PU-LWC offers reduced density and improved insulation properties. However, its performance is highly dependent on the water-to-cement (w/c) ratio, which significantly affects strength, durability, and workability. Unlike traditional concrete, the presence of polyurethane alters the internal structure and bonding behavior, making standard w/c ratio guidelines less applicable. Therefore, this study investigates the optimization of the w/c ratio in PU-LWC to achieve a balanced performance between lightweight characteristics and mechanical strength, contributing to the advancement of sustainable construction materials. The study examines the effects of different w/c ratios on the mechanical, physical, and durability properties of PU-LWC, aiming to enhance its performance for non-structural applications. Laboratory testing of PU-LWC samples with two w/c ratios (0.60 and 0.70), incorporating epoxy moulding compound (EMC) as a filler, reveals significant insights into the material's compressive strength, density, and water absorption. The results demonstrate that a higher w/c ratio improves early-stage strength and enhances polymer dispersion but also increases porosity and water absorption. The study concludes that a w/c ratio of 0.70 provides an optimal balance between strength and lightweight characteristics, making it a promising material for sustainable construction practices.

1. Introduction

The construction industry is increasingly focusing on sustainability and material efficiency to meet global demands for reduced environmental impacts and optimized performance. Conventional concrete, while widely used, has a high environmental footprint due to its significant resource consumption and carbon emissions during production [1]. To address this issue, the development of alternative construction materials such as polyurethane lightweight concrete (PU-LWC) has garnered attention, offering benefits such as reduced weight, improved energy efficiency, and the potential for incorporating industrial by-products [2].

This study investigates the optimization of the water-to-cement (w/c) ratio in polyurethane lightweight concrete to enhance its mechanical, physical, and sustainability properties. The study aims to determine how variations in the w/c ratio affect the compressive strength, density, water absorption, and overall durability of PU-LWC. Additionally, the incorporation of waste-derived fillers, such as epoxy moulding compound (EMC), is explored as a method for improving the material's performance while promoting sustainable construction practices [3].

The report presents experimental findings based on two w/c ratios (0.60 and 0.70), analyzing their impact on the properties of PU-LWC and offering recommendations for its potential applications in sustainable, non-structural construction [4] The study's significance lies in its contribution to the development of eco-engineered construction materials that support Sustainable Development Goals (SDGs) by promoting resource efficiency, waste reduction, and environmental sustainability [5].

2. Proposed Mix Design

For this experiment, two different water-to-cement (w/c) ratios were selected to produce polyurethane lightweight concrete (LWPU) with the raw materials specified in Table 1. The chosen w/c ratios are 0.60 and 0.70[14], aimed at investigating the effects of varying the water-to-cement ratio on the mechanical, physical, and durability properties of the polyurethane lightweight concrete.

Table 1 *The composition of raw materials for producing 0.1 of LWPU concrete*

Materials	w/c ratio 0.6	w/c ratio 0.7
Water, kg	0.516	0.603
PU, kg	1.292	1.292
EMC, kg	0.043	0.043
Cement, kg	0.862	0.862
Sand, kg	3.015	3.015
Hardener, kg	0.026	0.026

Both mixes are designed to evaluate the impact of different w/c ratios on the compressive strength, density, water absorption, and microstructure of polyurethane lightweight concrete. The higher water-to-cement ratio in Mix 2 (w/c 0.70) is expected to produce a lighter concrete structure with increased porosity compared to Mix 1 (w/c 0.60), which may result in a denser and stronger concrete. However, this study aims to achieve an optimal balance between strength and lightweight characteristics for sustainable lightweight concrete applications.

2.1 Mixing Process

The mixing process for the polyurethane lightweight concrete follows a systematic procedure to ensure uniform distribution of the materials and to achieve the desired consistency. The raw materials for both Mix 1 and Mix 2, as described in Table 1, were first weighed according to their respective proportions. The dry mix was mixed in a dry condition to achieve uniformity.

Next, the water was added to the dry mix according to the selected water-to-cement (w/c) ratio of either 0.60 or 0.70. After thorough mixing of the water with the fine aggregate, the polyurethane (PU) was added to the mixture. The polyol and isocyanate (PU) were mixed for approximately 10 seconds to ensure even distribution within the mix, followed by the hardener, which was used in small quantities to initiate the polymerization reaction was added to mixture[7].

After all ingredients were thoroughly mixed to form a consistent liquid binder, the mixture was poured into moulds of 100 mm × 100 mm × 100 mm dimensions. The moulds were placed in a controlled environment for a minutes to allow the mix to expand[8]. Following this, the surface of the mixture was pressed and covered to ensure the sample was compacted properly. The specimens were then removed from the moulds and subjected to air curing for 7 days and 28 days, in line with the curing protocol before being tested for mechanical and physical properties.

3. Compressive Strength

Compressive strength is a key indicator of the load-bearing capacity and overall structural performance of concrete. In this study, cube specimens with a size of 100 mm × 100 mm × 100 mm were made using two different water-to-cement (w/c) ratios: 0.60 and 0.70. The cubes were tested at 7 and 28 days using a Universal Testing Machine (UTM) to measure how much load they could handle before breaking. The compressive strength was calculated using the maximum load the cube could take, divided by the cross-sectional area refer equation 1.

$$Compressive\ Strength, MPa = \frac{Maximum\ load\ at\ failure, N}{Cross - sectional\ area, mm^2} \quad (1)$$

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The compressive strength results are summarized in Tables 2 and 3 for 7-day and 28-day curing periods, respectively. Additionally, the average compressive strength values are illustrated in Figure 1.

Table 2 *Compressive Strength Results at 7 Days*

w/c Ratio	Specimen	Failure Load (kN)	Compressive Strength (MPa)
	Cube 1	5.0	0.5
0.6	Cube 2	3.6	0.36
	Cube 3	4.0	0.4
Average		**4.2**	**0.42**
	Cube 1	6.3	0.63
0.7	Cube 2	7.2	0.72
	Cube 3	7.4	0.74
Average		**6.9**	**0.69**

At 7 days, the concrete mix with a w/c ratio of 0.60 had an average compressive strength of 0.42 MPa, while the mix with a w/c ratio of 0.70 had a higher average of 0.69 MPa. The higher w/c ratio in Mix 2 (0.70) allowed for better hydration and easier mixing, which improved its early strength.

Table 3 *Compressive Strength Results at 28 Days*

w/c Ratio	Specimen	Failure Load (kN)	Compressive Strength (MPa)
	Cube 1	6.7	6.7
0.6	Cube 2	7.0	7.0
	Cube 3	5.6	5.6
Average		6.4	6.4
	Cube 1	9.3	9.3
0.7	Cube 2	11.0	11.0
	Cube 3	9.5	9.5
Average		9.9	9.9

At 28 days, both mixes showed more strength development. The mix with a w/c ratio of 0.60 reached an average compressive strength of 0.64 MPa, while the mix with a w/c ratio of 0.70 reached 0.99 MPa. The mix with a higher w/c ratio continued to perform better showing that more water allowed for better hydration and a stronger matrix[9].

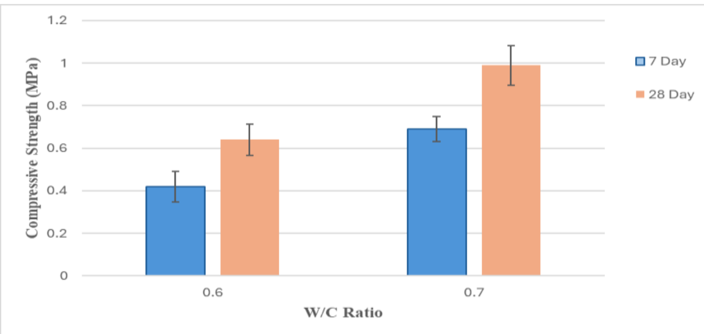

Fig. 1 *Compressive Strength Average Results*

Compared to other lightweight concrete, the strength values of polyurethane concrete are lower, as expected. Polyurethane concrete is designed to be lightweight, so it is not meant to have the same high strength as traditional concrete [10]. However, by optimizing the water-to-cement ratio, the compressive strength can be improved, especially for lightweight applications [6]. The trend seen in this study, where a higher w/c ratio leads to stronger concrete, supports this idea.

In conclusion, controlling the water-to-cement ratio is important for achieving the desired strength in polyurethane concrete. The mix with a w/c ratio of 0.70 showed the best compressive strength, making it suitable for lightweight and sustainable construction projects.

3.1 Density Test

The density of PULWC samples is calculated as the mass of the test specimen divided by its volume, with three samples tested for each mixture and the average value considered as the final density refers equation 2.

$$\text{Density, p=m/v} \tag{2}$$

Based on the density test results at 7 days, the polyurethane concrete with a water-cement ratio of 0.60 showed an average density of 1080 kg/m^3. The individual specimens had densities of 1150 kg/m^3, 1060 kg/m^3, and 1030 kg/m^3, indicating that the material has a relatively compact structure. The slight variation in values reflects differences in pore structure and material distribution within the samples. The higher density observed for the first specimen suggests slightly fewer pores, pointing to a denser mix. For the polyurethane concrete with a water-cement ratio of 0.70, the average density was 1026 kg/m^3, with individual specimens showing densities of 910 kg/m^3, 1110 kg/m^3, and 1060 kg/m^3. The lower average density suggests a higher porosity compared to the 0.60 mix, which is expected due to the increased water content that leads to more pore formation. The variation in densities further suggests that the water-cement ratio significantly impacts the material's structure, with higher water content resulting in lower density and a more porous concrete mix [11].

Table 4 *Density Test Result at 7 Days*

w/c Ratio	Specimen	Mass (kg)	Volume (m^3)	Density (kg/m^3)
	Cube 1	1.15	0.001	1150
0.6	Cube 2	1.06	0.001	1060
	Cube 3	1.03	0.001	1030
Average		**1.08**	**0.001**	**1080**
	Cube 1	0.91	0.001	910
0.7	Cube 2	1.11	0.001	1110
	Cube 3	1.06	0.001	1060
Average		**1.03**	**0.001**	**1026**

At 28 days, the polyurethane concrete with a water-cement ratio of 0.60 showed an average density of 1240 kg/m^3, with specimens recorded densities of 1320 kg/m^3, 1220 kg/m^3, and 1180 kg/m^3. This indicates that, as the concrete cured over time, its structure became more compact and denser, suggesting continued hydration and reduced porosity, likely due to the balance in water content and cement hydration at the lower water-cement ratio. For the 0.70 water-cement ratio mix, the average density was 1170 kg/m^3, with densities of 1040 kg/m^3, 1270 kg/m^3, and 1220 kg/m^3. The decrease in density compared to the 0.60 ratio indicates that the higher water content led to more pore formation, resulting in a lighter mix. The variation in density values across the specimens further highlights the influence of the water-cement ratio on the porosity and compactness of the concrete, with higher water content leading to a more porous structure even after 28 days of curing.

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Table 4 *Density Test Result at 28 Days*

w/c Ratio	Specimen	Mass (kg)	Volume (m^3)	Density (kg/m^3)
	Cube 1	1.32	0.001	1320
0.6	Cube 2	1.22	0.001	1220
	Cube 3	1.18	0.001	1180
Average		**1.24**	**0.001**	**1240**
	Cube 1	1.04	0.001	1040
0.7	Cube 2	1.27	0.001	1270
	Cube 3	1.22	0.001	1220
Average		**1.17**	**0.001**	**1170**

The average density test results for polyurethane concrete at 7 and 28 days, as shown in Figure 2, highlight the effects of the water-cement ratios of 0.6 and 0.7. At 7 days, the concrete with a water-cement ratio of 0.6 had an average density of 1080 kg/m^3, while the 0.7 ratio mix had a lower average density of 1026 kg/m^3. This shows that the mix with a lower water-cement ratio has a higher density, indicating better compactness and fewer voids. At 28 days, both mixes showed increased density, with the 0.6 ratio mix reaching an average of 1240 kg/m^3 and the 0.7 ratio mix achieving an average of 1170 kg/m^3. This increase in density over time reflects the continued hydration of the concrete, with the 0.6 ratio mix still maintaining a denser structure compared to the 0.7 ratio mix. The higher water content in the 0.7 ratio resulted in a more porous structure, which is consistent with the lower density values observed.

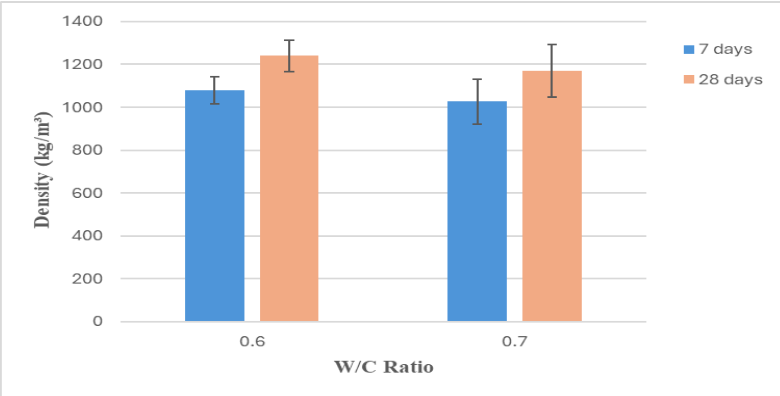

Fig. 2 *Density Test Average Results*

According to ACI 213R, concrete with a density below 2000 kg/m^3 is classified as lightweight concrete. The density values obtained in this study fall well within this range, confirming that the polyurethane concrete produced can be classified as lightweight. Therefore, the w/c ratio of 0.70 is more favorable for applications requiring reduced weight, although it still offers good mechanical performance for sustainable construction projects.

3.2 Water Absorption Test

The procedure involves drying a concrete specimen in an oven to a constant weight, cooling it to room temperature, and then immersing it in water for 24 hours. The increase in mass due to water uptake is then measured to determine the percentage of water absorption. In this study, the test follows standard practice using cubic specimens with dimensions of 100 mm × 100 mm, as recommended in related durability assessments (ASTM C642). These dimensions ensure consistent surface area and exposure conditions for moisture penetration analysis. The water absorption value is calculated refer equation 3

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$$Compressive\ Strength, MPa = \frac{Maximum\ load\ at\ failure, N}{Cross - sectional\ area, mm^2} \tag{3}$$

The water absorption test is conducted to evaluate the ability of concrete to resist moisture ingress, an important indicator of its durability and long-term performance. At 7 days, the polyurethane concrete with a water-cement ratio of 0.60 showed an average water absorption of 18.63%. The individual specimens recorded absorption percentages of 15.79%, 20.55%, and 19.54%, showing moderate variation. The differences in absorption values are due to slight variations in the pore structure and hydration process, but overall, the concrete exhibited a relatively balanced moisture ingress capacity. For the concrete mix with a water-cement ratio of 0.70, the average water absorption was higher at 20.86%, with individual specimens showing absorption values of 24.64%, 18.57%, and 19.36%. The higher water absorption in this mix indicates increased porosity and moisture retention compared to the 0.60 ratio mix, as the increased water content results in a more porous concrete structure, which allows more water to be absorbed into the material.

Table 5 *Density Test Result at 7 Days*

w/c Ratio	Specimen	Dry Mass, M_1 (g)	Saturated Mass, M_2 (g)	Water Absorption (%)
	Cube 1	1123.33	1300.74	15.79
0.6	Cube 2	1037.40	1250.56	20.55
	Cube 3	1003.97	1200.19	19.54
Average		**1054.9**	**1250.50**	**18.63**
	Cube 1	1043.29	1300.34	24.64
0.7	Cube 2	1265.24	1500.19	18.57
	Cube 3	1215.38	1450.65	19.36
Average		**1174.64**	**1417.06**	**18.63**

At 28 days, both mixes showed increased water absorption, with the 0.60 ratio mix achieving an average of 23.02% and the 0.70 ratio mix showing an average of 25.17%. The individual specimens recorded water absorption values of 19.79%, 25.36%, and 24.22% for the 0.60 ratio mix, and 30.29%, 22.83%, and 22.40% for the 0.70 ratio mix. The increase in water absorption over time reflects continued hydration of the concrete but also suggests that higher water content promotes greater moisture ingress, making the 0.70 mix more susceptible to moisture absorption.

Table 5 *Density Test Result at 28 Days*

w/c Ratio	Specimen	Dry Mass, M_1 (g)	Saturated Mass, M_2 (g)	Water Absorption (%)
	Cube 1	1321.57	1583.22	19.79
0.6	Cube 2	1220.47	1530.07	25.36
	Cube 3	1181.14	1467.28	24.22
Average		**1241.06**	**1526.86**	**23.02**
	Cube 1	1043.29	1359.34	30.29
0.7	Cube 2	1265.24	1554.19	22.83
	Cube 3	1215.38	1487.65	22.40
Average		**1174.64**	**1467.06**	**25.17**

As shown in Figure 3, the average water absorption results for both mixes at 7 and 28 days highlight the effects of the water-cement ratio on moisture absorption. The 0.6 ratio mix had an average absorption of 18.63% at 7 days and 23.02% at 28 days, while the 0.7 ratio mix had a higher absorption of 20.86% at 7 days and 25.17% at 28 days. This trend confirms that higher water content leads to increased porosity and a more permeable concrete structure [12].

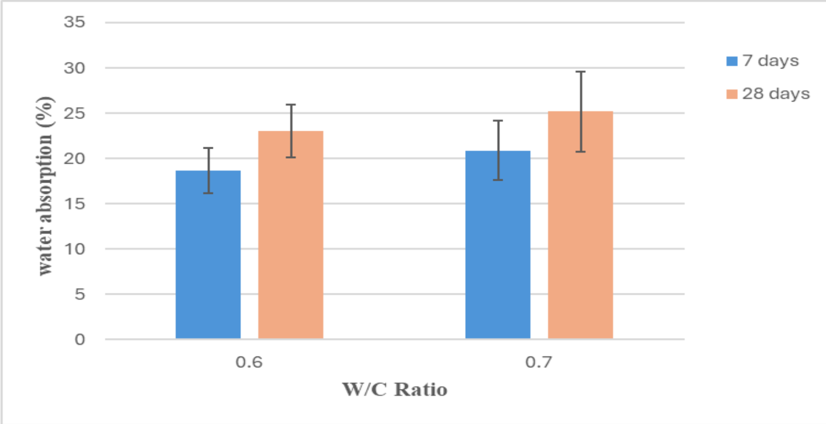
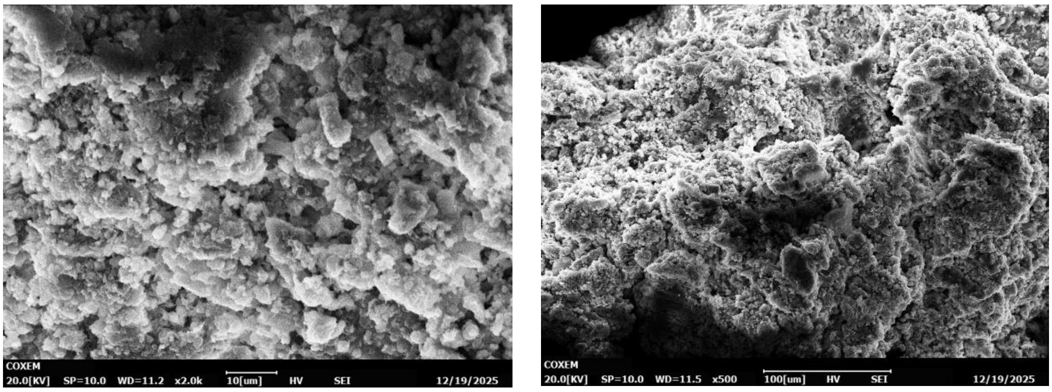


Fig. 3 *Water Absorption Average Result*

In conclusion, the polyurethane concrete with a lower water-cement ratio (0.60) exhibited better resistance to moisture absorption, indicating higher durability and a more compact structure. The mix with a higher water-cement ratio (0.70) showed greater susceptibility to moisture ingress, highlighting the importance of controlling the water content in the mix to optimize concrete durability especially for applications exposed to aggressive environments [13].

3.3 SEM/EDX Analysis

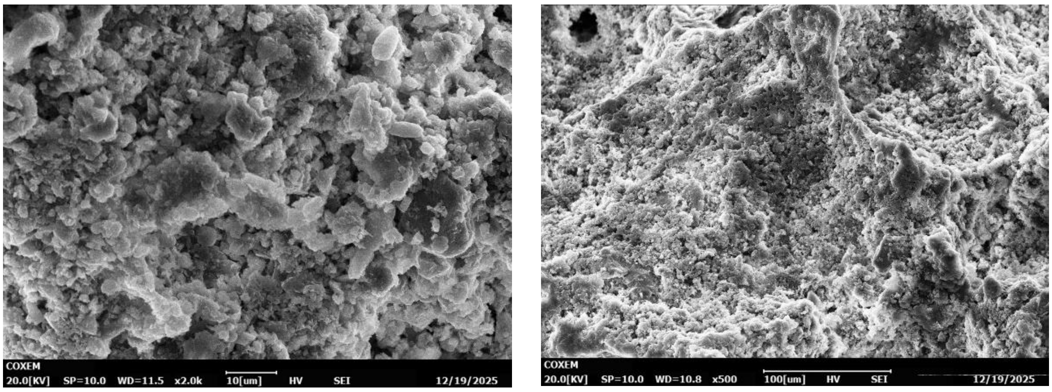
The SEM micrographs presented in Figure 4 show the microstructure of polyurethane lightweight concrete (PULWC) with a water-cement ratio of 0.6. At a magnification of 10 μm, the microstructure reveals a rough and porous surface texture. The presence of voids and irregularities indicates that polyurethane expansion during the curing process contributed to the formation of pores within the concrete. These pores are characteristic of the lightweight nature of the concrete [2]. At a higher magnification of 100 μm, the microstructure highlights a network of interconnected pores, with the cement matrix and polyurethane phase interacting. The porous structure observed at this magnification reflects the lower density and higher water absorption observed in the concrete, particularly due to the higher water-cement ratio. These observations provide insight into how the water-cement ratio affects the formation of the pore structure and its subsequent impact on the material's performance.



(a) **(b)**

Fig. 4 *SEM Micrograph of PULWC at 10 μm (a) and 100 μm (b) for W/C 0.6*

In Figure 5, the SEM micrographs for polyurethane lightweight concrete (PULWC) with a water-cement ratio of 0.7 are presented. At a magnification of 10 μm, a porous surface with irregularities is visible, similar to the structure seen in the 0.6 water-cement ratio mix. However, the pores appear to be larger and more interconnected, indicating a higher degree of porosity due to the increased water content in the mix [14].



(a) **(b)**

Fig. 5 *SEM Micrograph of PULWC at 10 µm (a) and 100 µm (b) for W/C 0.7*

The increased water-cement ratio in the 0.7 mix resulted in a more open and connected pore structure. At a magnification of 100 µm, the higher porosity is further evident. This increased porosity likely contributes to the higher water absorption and lower density observed in the 0.7 mix. The microstructure also shows less compact bonding between the cement matrix and polyurethane particles, which could affect the concrete's mechanical strength and durability [14].

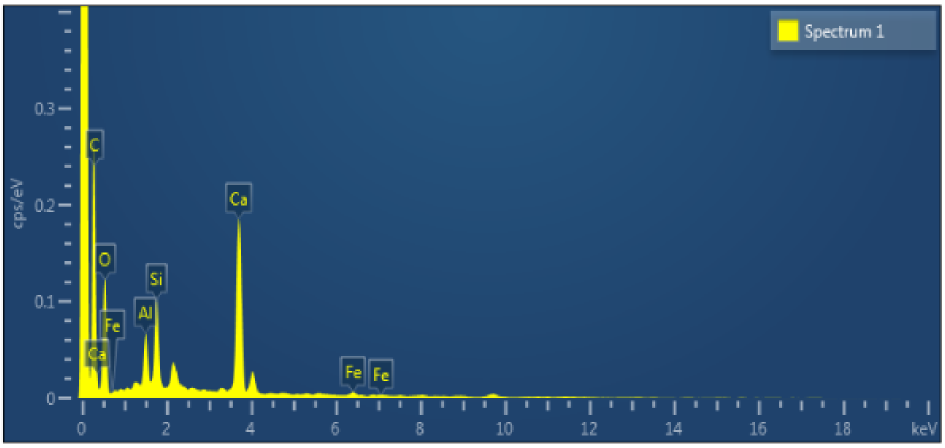


Fig. 6 *Graphical EDX Analysis on W/C 0.6*

The EDX analysis shown in Figure 7 for the water-cement ratio of 0.6 reveals the major elements present, which are carbon (C), oxygen (O), calcium (Ca), and silicon (Si). Carbon recorded the highest value at 47.72 wt%, indicating a significant presence of polyurethane within the concrete matrix. Oxygen was detected at a high level of 37.00 wt%, which is mainly associated with cement hydration products and oxygen-containing polymer compounds [5].

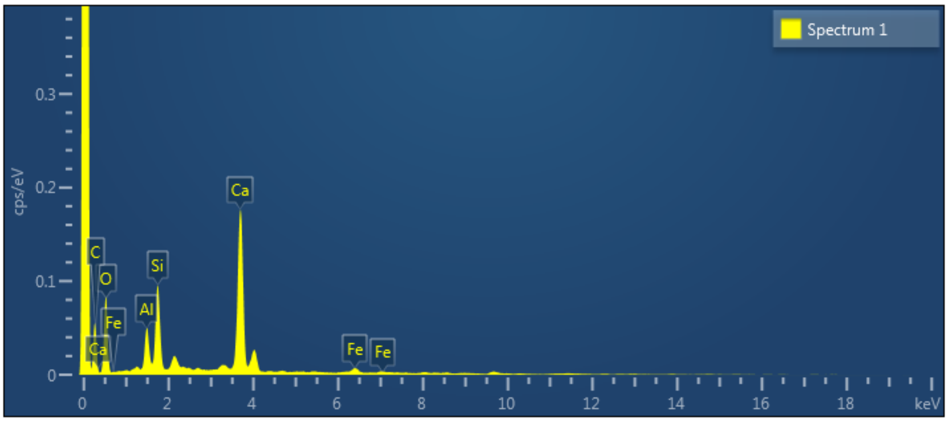


Fig. 7 *Graphical EDX Analysis on W/C 0.7*

The EDX analysis for the mix with a water-cement ratio of 0.7 (Figure 4.7) shows similar elements, but with increased levels of calcium (Ca) at 17.28 wt% and silicon (Si) at 5.50 wt%. These elements confirm the presence of cement hydration products and indicate that the cement and polyurethane phases are interacting more at the microstructural level compared to the 0.6 ratio mix [6]. The increased calcium content in the 0.7 mix suggests more cement hydration, while the higher carbon content indicates a stronger presence of polyurethane in the concrete matrix. This supports the observed higher porosity and the impact of the water-cement ratio on the concrete's structural integrity and performance [6]

4. Conclusion

By This study investigated the effect of the water-to-cement (w/c) ratio on the properties of polyurethane lightweight concrete incorporating epoxy moulding compound (EMC) as a filler. Two different w/c ratios, 0.60 and 0.70, were evaluated in terms of compressive strength, density, water absorption, and microstructural characteristics. The results showed that the polyurethane concrete with a w/c ratio of 0.70 achieved higher compressive strength at both 7 and 28 days compared to the mix with a w/c ratio of 0.60. This indicates that a higher water content promoted better cement hydration and improved interaction between the cement matrix and polyurethane phase. However, both mixes exhibited relatively low compressive strength compared to conventional structural concrete, confirming that the material is more suitable for lightweight and non-structural applications.

Density test results confirmed that all specimens fell within the lightweight concrete classification. The w/c 0.70 mix recorded a lower density due to increased pore formation, which is beneficial for reducing structural self-weight. Water absorption tests showed higher absorption at the higher w/c ratio, indicating increased porosity and moisture ingress potential. SEM analysis revealed a porous and non-uniform microstructure caused by polyurethane expansion, while EDX analysis confirmed that the elemental composition of both mixes was similar and dominated by carbon, oxygen, calcium, and silicon. This indicates that the observed differences in performance were mainly due to microstructural changes rather than chemical composition.

Overall, the study concludes that a w/c ratio of 0.70 provides a better balance between strength development and lightweight characteristics for polyurethane lightweight concrete, making it a suitable material for applications requiring reduced weight while maintaining mechanical performance.

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Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Zarul Adham, Hasnida Harun****; data collection:*** *Muhammad Zarul Adham;* ***analysis and interpretation of results:*** *Muhammad Zarul Adham, Hasnida Harun;* ***draft manuscript preparation:*** *Muhammad Zarul Adham, Hasnida Harun. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Gao, H., Liu, L., Yang, W., Dong, Y., & Liu, H. (2024). *Experimental study on mechanical properties of polyurethane-based composites*. Case Studies in Construction Materials, 21, e03907. https://doi.org/10.1016/j.cscm.2024.e03907

[2] Liu, B., Shi, J., Sun, M., He, Z., Xu, H., & Tan, J. (2020). Mechanical and permeability properties of polymer-modified concrete using hydrophobic agent. *Journal of Building Engineering*, *31*, 101337. https://doi.org/10.1016/j.jobe.2020.101337

[3] Molari, L., Coppolino, F. S., & García, J. J. (2020). Arundo donax: *A widespread plant with great potential as sustainable structural material*. Construction and Building Materials, 268, 121143. https://doi.org/10.1016/j.conbuildmat.2020.121143

[4] Leong, W. Y., Leong, Y. Z., & Leong, W. S. (2023). Green Building Initiatives in ASEAN Countries., *80*, 01–06. https://doi.org/10.1109/eee-am58328.2023.10395261

[5] Priya., Ghosh, C., & Thenmozhi, M. (2024b). Impact of fintech and financial inclusion on sustainable development goals: Evidence from cross country analysis. *Finance Research Letters*, *72*, 106573. https://doi.org/10.1016/j.frl.2024.106573

[6] Huo, T., Xue, J., & Fu, Z. (2022). Analysis of the Performances and Optimization of Polyurethane Concrete with a Large Percentage of Fly Ash. *Fluid Dynamics & Materials Processing*, *19*(2), 437–450. https://doi.org/10.32604/fdmp.2022.020696
[7] Mohi-Ud-Din, M. M., Khan, M. Z. N., Hafeez, M. O., Cheema, U. S., Khokhar, S. A., & Arshad, M. H. (2024). Exploring the potential of rigid polyurethane foam waste in structural lightweight concrete. *Next Materials*, *6*, 100399. https://doi.org/10.1016/j.nxmate.2024.100399
[8] Rodrigo-Bravo, A., Pavía, S., Calderón-Carpintero, V., Cuenca-Romero, L. A., & Gutiérrez-González, S. (2024). Valorisation of gypsum boards with polyurethane waste to promote their circular economy. *Resources Conservation & Recycling Advances*, 200240. https://doi.org/10.1016/j.rcradv.2024.200240
[9] Assaad, J. J., & Mir, A. E. (2020). Durability of polymer-modified lightweight flowable concrete made using expanded polystyrene. *Construction and Building Materials*, *249*, 118764. https://doi.org/10.1016/j.conbuildmat.2020.118764
[10] Suttaphakdee, P., Dulsang, N., Lorwanishpaisarn, N., Kasemsiri, P., Posi, P., & Chindaprasirt, P. (2016). Optimizing mix proportion and properties of lightweight concrete incorporated phase change material paraffin/recycled concrete block composite. *Construction and Building Materials*, *127*, 475–483. https://doi.org/10.1016/j.conbuildmat.2016.10.037
[11] Aïtcin, P. (2015). The importance of the water–cement and water–binder ratios. In *Elsevier eBooks* (pp. 3–13). https://doi.org/10.1016/b978-0-08-100693-1.00001-1
[12] Zajac, M., Skocek, J., Stabler, C., Bullerjahn, F., & Haha, M. B. (2018). Hydration and performance evolution of belite–ye'elimite–ferrite cement. *Advances in Cement Research*, *31*(3), 124–137. https://doi.org/10.1680/jadcr.18.00110
[13] Song, H., & Saraswathy, V. (2007). Corrosion Monitoring of Reinforced Concrete Structures – a review. *International Journal of Electrochemical Science*, *2*(1), 1–28. https://doi.org/10.1016/s1452-3981(23)17049-0
[14] Zhai, D., Sun, Q., Wang, Y., & Li, J. (2024). Microstructure and mechanical performance of polyurethane-fly ash composites (PU-FAC) under different effect factors. *Case Studies in Construction Materials*, *21*, e03405. https://doi.org/10.1016/j.cscm.2024.e03405