An Innovative Approach on Recycle Foam Concrete as a Sustainable Alternative with the addition of Nano Titanium Dioxide TiO_2 on the Properties of Foam Concrete

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ABSTRACT

Sustainability and construction waste recycling have become crucial topics today in response to the growing environmental challenges and the increasing accumulation of waste. Therefore, it is essential to explore innovative solutions that improve the sustainability of concrete mixes. An effective approach is the use of Lightweight Foamed Concrete (LFC), a revolutionary new material that is considered a viable solution for the reduction of the weight of conventional concrete. This research focuses on the study of the effect of replacing 50% of virgin sand by volume with Recycled Foam Concrete (RFC) waste crushed at four gradation levels with aggregate sizes between 12.5-9.5 mm, 9.5-4.75 mm, 4.75-2.36 mm, and 2.36-1.18 mm, and the effect of adding 0.5% Nano titanium dioxide TiO_2 by weight of cement. The water-to-cement and cement-to-aggregate ratio were maintained at 0.45 and 1:1.3, respectively. Nanoparticles are incorporated into Foam Concrete (FC) to enhance its strength, due to their beneficial properties, such as their small particle size and high reactivity. The results conclude on the optimal sizes of RFC with the addition of Nano TiO_2 for use in FC mixes that enhance compressive strength and increase carbonation compared to traditional FC mixes.

Keywords-Recycled Foam Concrete (RFC) waste; Nano TiO_2; compressive strength

I. INTRODUCTION

Concrete is one of the most commonly used materials worldwide with an annual production of around 12 billion tons and it plays a significant role in the global construction industry. It is estimated that it generates more than 31,000 tons of waste every year and it is considered one of the most important environmental threats [1, 2]. Construction waste is the debris produced from the tearing down or dismantling of buildings, roads, bridges, and other constructions and it consists of materials like concrete, metal, glass, bricks, wood, plastics, and other. The annual increase of construction waste and the need for natural resource consumption minimization triggers innovative solutions for construction waste recycling [3, 4]. Additionally, there is an increasing demand for lightweight materials that are adaptable, versatile, high-performing, and environmentally friendly intended for lightweight and sustainable concrete production [5-7]. Studies have concluded on the incorporation of recycled waste materials, such as rubber tires, crushed glass, and crushed clay bricks, as partial replacements for aggregates in concrete for the construction of eco-friendly, lightweight building materials. It was found that the dry density of concrete decreased by 4%, 21.7%, and 31.7% when crushed glass, clay bricks, and rubber tires were used instead of sand, respectively. Waste rubber demonstrated excellent performance in terms of resistance to sulfate, heat, and impact, while glass powder and finely ground clay bricks improved the mechanical properties, with glass increasing strength by 33% and clay bricks offering a slight improvement. Additionally, these materials contributed to higher thermal resistance compared to traditional concrete. Given their lower particle density relative to conventional aggregates, they are well-suited for producing lightweight concrete for both structural and non-structural applications [8]. Aerated concrete, commonly known as FC, is a concrete characterized by its lightweight nature and versatility and it is constructed from cement, water, fine aggregate, and foam [9-11]. The benefits of FC go beyond its resistance to fire and seismic activity. FC blocks are widely preferred for wall construction thanks to their superior thermal and sound insulation capabilities. Its versatility enables its use for filling voids behind archways, repairing damaged sewer systems, and masonry unit manufacturing for various needs [12, 13]. LFC is suitable for multiple applications, such as floor construction, and building of culverts and bridges. Its light weight reduces the self-weight of structural concrete, and thus reduces the weight of dead load members, such as foundations, columns, and beams. Additionally, the cost of construction projects is lowered because of the reduced use of materials. Its distinctive features include the minimal consumption of coarse aggregate, high flow ability, resistance to fire, and excellent sound and thermal insulation. Moreover, it provides a lower concrete density, ranging between 400 and 1850 kg/m³, which is significantly lighter than standard lightweight concrete. As a result, it reduces transportation costs and decreases the number of construction workers and construction effort [14-18].

The highly porous nature of FC reduces its effectiveness, however, it has been proven that the LFC matrix can be strengthened with the incorporation of various nanoparticles. Although the utilization of nanomaterials has previously demonstrated a substantial improvement in durability characteristics and mechanical performance, the use of Nano TiO_2 on LFC has not been fully explored leaving uncertainty about its influence on LFC durability properties [19, 20]. This research focuses on the effects of RFC waste as a partial replacement of natural aggregate, by crushing it into various sizes, and the mechanical and environmental impact of the addition of Nano TiO_2 by weight of cement. The study aims to construct sustainable FC and reduce the volume of construction waste.

II. MATERIALS

A. Cement

Following the Iraqi standard specification regarding physical and chemical composition requirements [21], Ordinary Portland Cement (OPC) CEM I- 42.5R was used in this study.

B. Sand

The sand utilized in the present study was sourced from a nearby riverbed, with particles larger than 2.36 mm being excluded. These larger particles were removed to prevent them from settling in the lightweight mix, which could cause the foam to collapse during mixing. The natural sand deployed in this study consisted of particles with uniform size as determined with sieve analysis [22].

C. Recycled Foam Concrete

The RFC employed in the current paper was derived from factory waste. The preparation process involved the following steps:

1. The concrete samples were crushed using a crusher and a hammer into small particles of the desired size.
2. The crushed concrete was then sieved to obtain particles that resembled the natural coarse and fine aggregates, as shown in Table I and Figure 1.

TABLE I. FOUR GRADATION LEVELS OF CRUSHED RFC

No	Sieve size (mm)	Passing (mm)	Retained (mm)
1	12.5-9.5	12.5	9.5
2	9.5-4.75	9.5	4.75
3	4.75-2.36	4.75	2.36
4	2.36-1.18	2.36	1.18

Fig. 1. Crushed RFC as aggregate.

D. Water

Drinking water was used for mixing and curing purposes [23].

E. Foaming Agent

PA-1 foaming agent was utilized in this paper, which was initially diluted in water at 1:30 and afterwards aerated to produce stable foam at the density of 63-70 kg/m^3 [24].

F. Nano Titanium Dioxide

The physical analysis of the Titanium dioxide nanoparticles that were imported is displayed in Table II.

TABLE II. PROPERTIES OF NANO TiO_2

Properties	Specifications
Appearance	White
Purity	99.9%
Form	Powder
Density	30-50 g/m^2

III. PREPARING FOAM CONCRETE MIXTURE

A. Mixing, Casting, and Curing

A variety of mixes were prepared in this research to determine the appropriate proportions of the mix components, with a cement-to-sand ratio of 1:1.3 and a water-to-cement ratio of 0.45. Five concrete mixes were studied: one reference mix and four mixes including RFC of different sizes as partial replacement of natural aggregates at 50% by volume, and Nano TiO_2 at 0.5% by weight of cement. The consistency of the mortar base mix was fixed to a value between 220-240 mm. The diameter of the mixture was measured by filling a cylinder with a diameter of 75 mm and a height of 150 mm. The laboratory results demonstrated that the addition of foam to the fresh mortar mixture reduced the spread diameter. This reduction is attributed to the increased adhesion between the foam bubbles, which limits the mixture's flow ability and the solid particles. The FC was casted into cubic molds with dimensions of 100×100×100 mm and left to dry in the air for 24 hours before removing the formwork. As soon as the specimens were removed from the molds, they were rolled with plastic sheet and wrapped well to prevent an exposure to moisture until testing. This type of processing is called Sealed Curing and is typical for the FC industry [25, 26]. The mixture design is depicted in Table III, given that cement content was 352.16 kg/m^3, and water-to-cement ratio was 0.45 for all mixes.

TABLE III. MIX DESIGN

Mix	**Materials**							
	Sand	**RFC (kg/m^3)**	**Nano TiO_2 (%)**	**Added water**	**Mortar density (kg/m^3)**	**Flow Test (cm)**	**Foam (dm^3)**	**Fresh density (kg/m^3)**
MR	457.6	0	0	0.67	2135	23.5	546.6	1060
M1	228.8	81.4	0.5	4.8	1890	23	562.3	1035
M2	228.8	88	0.5	33.6	1955	23	558.7	1030
M3	228.8	103.2	0.5	13.44	2015	22.5	574.3	1035
M4	228.8	177.6	0.5	46	2035	22	525.9	1050

B. Testing

1) Compressive Strength

Following the standard specification BS EN 12390-3:2019, three cubes with a size of 100×100×100 mm were used, and the average of the sample was taken at 7, 28 and 90 days [27].

2) Carbonation Depth

The Carbonation assessment was performed with the application of a phenolphthalein solution onto the freshly broken prism face [28].

IV. RESULTS AND DISCUSSION

A. Compressive Strength

The results demonstrated that the compressive strength of the mixes containing RFC with coarse sizes of 12.5-9.5 and 9.5-4.75 mm, and Nano TiO2 was less than the compressive strength of the MR mix. This finding can be attributed to the ununiform distribution of the RFC and nanomaterials [8]. On the contrary, the addition of Nano TiO_2 to mixes with RFC of finer sizes, such us 4.75-2.36 and 2.36-1.18 mm, showed higher values of compressive strength compered to the MR mix. TiO_2 can fill pores and it is proposed for strength development and reduced permeability due to the increased density of the mixture, the increased material bonding strength, and the refinement of voids [29]. The results are illustrated in Figure 2.

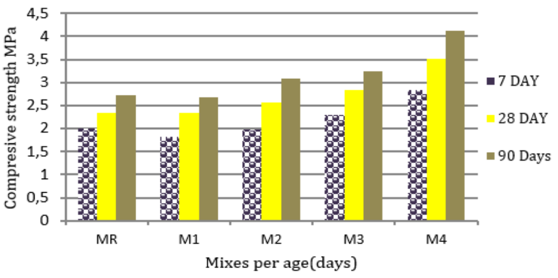

Fig. 2. Compressive strength of FC mixes per age (days).

B. Carbonation Depth

The results demonstrated that the carbonation depth of FC mixes is proportional to the sizes of the recycled aggregates used as a partial replacement of natural sand. Additionally, all FC mixes exhibited higher carbonation readings compared to the reference mix, MR. These results can be attributed to the 50% by volume replacement of natural sand with RFC. Lightweight aggregates, particularly those that are recycled, tend to absorb more carbon dioxide because of their open pores and cellular structure. The results showed that the mixes with fine aggregation level, such as 4.75-2.36 and 2.36-1.18 mm, had increased carbonation depth. Moreover, they revealed that the mixes containing coarse sizes, such as 12.5-9.5 and 9.5-4.75 mm, are less reactive to carbon dioxide due to their lower porosity and smaller surface area exposed to CO_2, which reduces the penetration of carbon. The results also disclosed that the carbonation depth increases with the age because of the/its exposure to CO_2 and environmental conditions. The results are depicted in Figure 3.

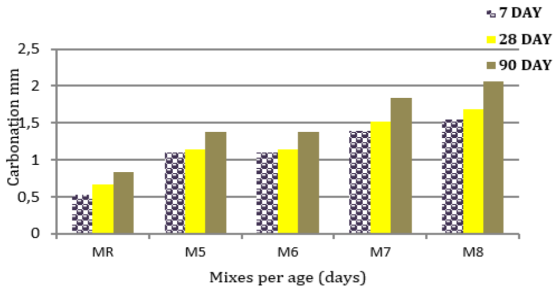

Fig. 3. Carbonation depth of FC mixes per age (days).

V. COMPARISON WITH PREVIOUS WORKS

Authors in [29] investigated the effect of thermostone blocks and ceramic tiles as a partial substitution of fine aggregate in FC. Three volume replacement rates of sand along with each waste material were evaluated, 25%, 50%, and 75%, and reached to an improvement of the compressive strength of up to 10.15 MPa. Authors in [20] investigated the effect of Titanium Dioxide Nanoparticles (TNPs) in FC mixes with a target dry density of 980 kg/m^3. Constant cement-to-filler and water-to-cement ratios of 1:1.5 were used. Six mixes with TNP weight fractions of 0% (control mix), 1%, 2%, 3%, 4%, and 5% were produced and showed superior improvement in compressive strength.

VI. CONCLUSIONS

The effects of using various sizes of Recycled Foam Concrete (RFC) as a replacement of natural sand with the addition of Nano TiO_2 on the properties of Lightweight Foamed Concrete (LFC) were examined in this study. Replacing 50% of the aggregate volume with crushed Foam Concrete (FC) of various sizes, combined with the addition of Nano TiO_2, resulted in increased strength values for all mixes compared to the reference mix (MR) at 28 days of age. This improvement can be attributed to the filling of pores that promotes strength development and reduces the permeability of the cement paste. The optimal size range for the crushed FC was found to be between 2.36 mm and 1.18 mm, which achieved the highest strength due to the activity and homogeneity of fine particles. The addition of Nano TiO_2 led to the increase of the mixture's density, the increase of the material's bonding strength, and the refinement of voids. The carbonation depth increased for all the mixes containing various sizes of RFC at the 28th day of age compared to the reference mix. This improvement can be attributed to the capillary action in FC that occurs due to the presence of a network of fine interconnected pores within its structure, allowing the movement of water and gases, such as carbon dioxide. Additionally, the nature of lightweight RFC typically exhibits greater porosity compared to natural aggregates that facilitates carbon dioxide penetration.

REFERENCES

[1] A. Kalpavalli and D. S. M. Naik, "Use of Demolished Concrete Wastes As Coarse Aggregates in High Strength Concrete Production," *International Journal of Engineering Research & Technology*, vol. 4, no. 7, Jul. 2015.

[2] A. M. Bravo-German, I. D. Bravo-Gómez, J. A. Mesa, and A. Maury-Ramírez, "Mechanical Properties of Concrete Using Recycled Aggregates Obtained from Old Paving Stones," *Sustainability*, vol. 13, no. 6, Jan. 2021, Art. no. 3044, https://doi.org/10.3390/su13063044.

[3] R. Q. Fawzi and H. K. Awad, "The Influence of Polypropylene Fiber and Silica Fume on the Mechanical Properties of No-Fine Concrete with Recycled Aggregate," *E3S Web of Conferences*, vol. 427, 2023, Art. no. 02002, https://doi.org/10.1051/e3sconf/202342702002.

[4] Z. A. Hussain and N. M. F. Aljalawi, "Some Properties of Reactive Powder Concrete Contain Recycled Glass Powder," *Journal of Engineering*, vol. 28, no. 10, pp. 42–56, Oct. 2022, https://doi.org/10.31026/j.eng.2022.10.04.

[5] D. J. Kazem and N. M. Fawzi, "Effect of Sustainable Materials on Some Properties of Pervious Concrete," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 14039–14043, Jun. 2024, https://doi.org/10.48084/etasr.7193.

[6] Q. J.-A. Hachim and N. M. Fawzi, "The Effect of Different Types of Aggregate and Additives on the Properties of Self-Compacting Lightweight Concrete," *Journal of Engineering*, vol. 18, no. 08, pp. 875–888, Aug. 2012, https://doi.org/10.31026/j.eng.2012.08.02.

[7] T. A. Abdalla, D. O. Koteng, S. M. Shitote, and M. Matallah, "Mechanical and Durability Properties of Concrete Incorporating Silica Fume and a High Volume of Sugarcane Bagasse Ash," *Results in Engineering*, vol. 16, Dec. 2022, Art. no. 100666, https://doi.org/10.1016/j.rineng.2022.100666.

[8] S. H. Helmy, A. M. Tahwia, M. G. Mahdy, M. Abd Elrahman, M. A. Abed, and O. Youssf, "The Use of Recycled Tire Rubber, Crushed Glass, and Crushed Clay Brick in Lightweight Concrete Production: A Review," *Sustainability*, vol. 15, no. 13, Jan. 2023, Art. no. 10060, https://doi.org/10.3390/su151310060.

[9] A. W. Ali and N. M. Fawzi, "Production of Light Weight Foam Concrete with Sustainable Materials," *Engineering, Technology & Applied Science Research*, vol. 11, no. 5, pp. 7647–7652, Oct. 2021, https://doi.org/10.48084/etasr.4377.

[10] H. H. A. Al–Hail and N. M. Fawzi, "Carbon Fiber Effect on Compressive Strength of Lightweight Foamed Concrete," *Journal of Engineering*, vol. 30, no. 8, pp. 34–47, Aug. 2024, https://doi.org/10.31026/j.eng.2024.08.03.

[11] S. A. Khawaja, U. Javed, T. Zafar, M. Riaz, M. S. Zafar, and M. K. Khan, "Eco-Friendly Incorporation of Sugarcane Bagasse Ash as Partial Replacement of Sand in Foam Concrete," *Cleaner Engineering and Technology*, vol. 4, Oct. 2021, Art. no. 100164 https://doi.org/10.1016/j.clet.2021.100164.

[12] B. Kado, S. Mohammad, Y. H. Lee, P. N. Shek, and M. A. A. Kadir, "Effect of Curing Method on Properties of Lightweight Foamed Concrete," *International Journal of Engineering & Technology*, vol. 7, no. 2.29, pp. 927–932, May 2018, https://doi.org/10.14419/ijet.v7i2.29.14285.

[13] A. Raj, D. Sathyan, and K. M. Mini, "Physical and Functional Characteristics of Foam Concrete: A Review," *Construction and Building Materials*, vol. 221, pp. 787–799, Oct. 2019, https://doi.org/10.1016/j.conbuildmat.2019.06.052.

[14] J. Xiao, W. Li, and C. Poon, "Recent Studies on Mechanical Properties of Recycled Aggregate Concrete in China—A Review," *Science China Technological Sciences*, vol. 55, pp. 1463–1480, Jun. 2012, https://doi.org/10.1007/s11431-012-4786-9.

[15] M. A. O. Mydin, N. MdNoordin, A. S. M. Said, and N. Mohamad, "Preliminary Study of Low Densities Lightweight Foamed Concrete Brick for Non-Load-Bearing Wall System," *Journal of Materials and Environmental Sciences*, vol. 9, no. 5, pp. 1405–1410, 2018.

[16] M. H. Nensok, M. A. O. Mydin, and H. Awang, "Investigation of Thermal, Mechanical and Transport Properties of Ultra Lightweight Foamed Concrete (ULFC) Strengthened with Alkali Treated Banana Fibre," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 86, no. 1, pp. 123–139, Oct. 2021.

[17] N. Song, Z. Li, W. Yi, and S. Wang, "Properties of Foam Concrete with Hydrophobic Starch Nanoparticles as Foam Stabilizer," *Journal of Building Engineering*, vol. 56, Sep. 2022, Art. no. 104811, https://doi.org/10.1016/j.jobe.2022.104811.

[18] F. A. Salih, F. Usman, G. Hayder, and Y. Al-Ani, "Evaluation of Some Beneficial Environmental Impacts and Enhanced Thermal Properties Resulting from Waste Plastic Integration into Concrete," *Annales de Chimie - Science des Matériaux*, vol. 47, no. 3, pp. 165–178, Jun. 2023, https://doi.org/10.18280/acsm.470306.

[19] A. A. Sattar, M. A. O. Mydin, and R. Omar, "Influence of Titanium Dioxide (TiO2) Nanoparticles on Durability Properties of Lightweight Foamed Concrete," *Journal of Advanced Research in Applied Mechanics*, vol. 109, no. 1, pp. 122–136, Oct. 2023, https://doi.org/10.37934/aram.109.1.122136.

[20] M. A. Othuman Mydin *et al.*, "Use of Calcium Carbonate Nanoparticles in Production of Nano-Engineered Foamed Concrete," *Journal of Materials Research and Technology*, vol. 26, pp. 4405–4422, Sep. 2023, https://doi.org/10.1016/j.jmrt.2023.08.106.

[21] *Iraqi Specification No. 5: Portland Cement,* Baghdad, Iraq: Central Organization for Standardization & Quality Control, 2019.

[22] *Iraqi Specification No. 45: Aggregates of Natural Resources Used for Concrete and Construction*, Baghdad, Iraq: Central Organization for Standardization & Quality Control, 1980.

[23] *Iraqi Specification No. 1703: Water Used in Concrete,* Baghdad, Iraq: Central Organization for Standardization & Quality Control, 2018.

[24] M. Z. Al-mulali, H. Awang, H. P. S. Abdul Khalil, and Z. S. Aljoumaily, "The Incorporation of Oil Palm Ash in Concrete as a Means of Recycling: A Review," *Cement and Concrete Composites*, vol. 55, pp. 129–138, Jan. 2015, https://doi.org/10.1016/j.cemconcomp.2014.09.007.

[25] H. Awang and Z. S. Aljoumaily, "Influence of Granulated Blast Furnace Slag on Mechanical Properties of Foam Concrete," *Cogent Engineering*, vol. 4, no. 1, Jan. 2017, Art. no. 1409853, https://doi.org/10.1080/23311916.2017.1409853.

[26] *BS EN 12390-7:2009, Testing Hardened Concrete - Part 7: Density of Hardened Concrete*, UK: British Standards Institution, 2019.

[27] *BS EN 12390-3:2019, Testing Hardened Concrete - Part 3: Compressive Strength of Test Specimens*, UK: British Standards Institution, 2019.

[28] C. Pico-Cortés and Y. Villagrán-Zaccardi, "Unraveling the Interplay of Physical-Chemical Factors Impacting the Carbonation Performance of Recycled Aggregate Concrete," *Materials*, vol. 16, no. 16, Aug. 2023, Art. no. 5692, https://doi.org/10.3390/ma16165692.

[29] Z. A. Shareef, S. Y. Ahmed, and O. M. Abdulkareem, "Potential Use of Wastes of Thermostone Blocks and Ceramic Tiles as Recycled Aggregates in Production of Foam Concrete," *Civil Engineering and Architecture*, vol. 11, no. 3, pp. 1280–1296, May 2023, https://doi.org/10.13189/cea.2023.110314.