

Synergistic Effects of Multiple Industrial By-product Constituents on the Performance of Hybrid Concrete Mixtures

Nuril Izzeaty Ishak^{1,2 *}, Mohd Fadzil Arshad², Nurul Hana Mohamad Zaini¹

¹Faculty of Built Environment, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia.

²Institute for Infrastructure Engineering and Sustainable Management (IIESM), Universiti Teknologi MARA, 40450 Shah Alam, Malaysia.

***Corresponding Author**

DOI: <https://doi.org/10.51583/IJLTEMAS.2026.150900145>

Received: 01 October 2026; Accepted: 06 October 2026; Published: 23 October 2026

ABSTRACT

The transition toward eco-efficient construction requires reducing the reliance on ordinary Portland cement (OPC) and natural aggregates. This study evaluates the physical performance of four sustainable hybrid concrete mixtures utilizing multiple industrial by-products and renewable materials under a controlled water-to-binder ratio of 0.35 and superplasticizer dosage of 1.5%. OPC was partially replaced at a constant volume of 60% using varying ternary combinations of Ground Granulated Blast-furnace Slag (GGBS), Rice Husk Ash (RHA), and Metakaolin (MK). The RHA was produced at 550°C, while MK was calcined at 700°C, and both materials were subsequently sieved to pass 150 µm. This study investigates the influence of fine aggregate variations, including 1.18 mm and 425 µm quarry dust sand, together with 14 mm gravel, and evaluates the effect of incorporating 1% coconut fiber on strength and water absorption performance at 7, 14, 21 and 28 days of curing. The GGBS-RHA hybrid concrete containing 1.18 mm quarry dust sand achieved the highest compressive-strength gains, while the fiber-rich GGBS-RHA mixture containing 425 µm quarry dust sand showed consistent strength development as curing age increased. The incorporation of 1% coconut fiber in the MK-RHA system, including 1.18 mm quarry dust sand, achieved optimum performance relative to the control. The water absorption properties of fiber-rich GGBS-RHA mixtures also showed a lower rate than the control for both quarry dust sand sizes, indicating improved resistance to water ingress. Conversely, MK-RHA mixtures give inconsistent water absorption rates, potentially due to the high fineness and water demand from RHA and MK. Overall, the results demonstrate that highly complex hybrid mixtures can meet structural concrete classifications while promoting the use of by-products and renewable materials.

Keywords: Hybrid Concrete Mixtures, RHA, GGBS, Metakaolin, Compressive Strength, Water Absorption

INTRODUCTION

The global demand for concrete continues to impose a severe environmental burden, primarily through extensive greenhouse gas emissions and the depletion of natural resources. Ordinary Portland cement (OPC) manufacturing contributes significantly to global carbon emissions because of high energy consumption and the carbon dioxide (CO₂) released during clinker production. In response, sustainable structural concrete design has increasingly focused on using supplementary cementitious materials (SCMs) and industrial by-products to reduce reliance on OPC and improve resource efficiency in concrete production (Neves et al., 2023). Researchers have widely investigated SCM binder materials such as ground granulated blast-furnace slag (GGBS), rice husk ash (RHA), and metakaolin (MK) for their potential to improve concrete performance through pozzolanic reactions, filler effects, and microstructural refinement. Previous studies show that these materials can enhance compressive strength, reduce permeability, and improve durability when incorporated at suitable replacement levels (Cai et al., 2026). However, SCM effectiveness depends heavily on chemical composition, particle characteristics, replacement proportion, and interactions with other concrete constituents.

In addition to SCMs, researchers have also explored alternative aggregate materials, such as quarry dust, to reduce dependence on natural river sand. Quarry dust production emits 28 kg/ton of CO₂, lower than OPC production, which accounts for 950 kg/ton. Quarry dust, a by-product of aggregate production, has significant potential as a fine-aggregate replacement because it is readily available and has a suitable mineral composition (AL-Kharabsheh et al., 2022). Although it significantly reduces embodied energy and greenhouse gas emissions, using quarry dust as a fine-aggregate replacement results in poor strength and durability performance (Pakkiyachandran & Sathiparan, 2025). Most studies using quarry dust have corroborated its positive influence on the mechanical and durability properties of concrete. Aref et al. (2025) mentioned that including 50% quarry dust by weight of sand did not significantly affect the physical and mechanical performance of concrete. However, the performance of concrete containing quarry dust may improve with additional admixtures to achieve optimal workability and strength (Altheeb, 2022).

Furthermore, the incorporation of natural fibres, such as coconut fiber (CF), has attracted growing interest because they can enhance crack resistance and support the development of sustainable composites. An early study by Pogosa et al. (2018) reported that adding CF to the mixture could increase the 28-day compressive and flexural strength of fibre-reinforced concrete up to 20%. CF offers greater resistance to external stresses because it resists decay, rust, and fungal growth (Nawab et al., 2023). A study by Shah et al. (2021) and Bediako et al. (2025) found that adding 1% CF by volume, with a 10 mm length, could improve the compressive strength of normal plain concrete. It was also supported by Elbashiry and Osman (2023) that including CF as low as 0.5% enhanced the tensile and flexural strength of the concrete. This is because coconut fiber offers promising properties such as high lignin (40-45%) and cellulose (32-44%) content, moisture content (up to 8%), high strength performance (15-24%) and enhanced tensile strength (up to 200 MPa) (Manuta et al., 2026). However, combining multiple sustainable materials may introduce complex interactions that affect concrete performance, such as mechanical and water-transport behaviour.

Although numerous studies have investigated individual sustainable materials in concrete, most existing research focuses on the influence of a single replacement material or a specific material combination. Few studies have comparatively evaluated hybrid sustainable concrete mixtures with different combinations of SCMs, alternative aggregates, and natural fibres under similar mixture conditions. The combination of various by-product materials, often called hybridization, is described as a composite of two or more types of materials rationally combined in a mix design to produce a mixture that develops benefits from each material and delivers very good properties. As a result, selecting an optimum sustainable concrete mixture that balances workability, strength development, and water absorption performance remains challenging. Therefore, this study aims to comparatively evaluate the performance of sustainable concrete mixtures incorporating different combinations of GGBS, RHA, metakaolin, quarry dust sand, and coconut fiber. This study investigates the effects of these material combinations on compressive strength development and water absorption properties. The findings provide practical insights into the suitability of different combinations of sustainable materials for concrete production and contribute to the development of environmentally responsible construction materials.

Problem Statement

The concrete industry faces mounting pressure to transition to sustainable, low-carbon construction practices, driven mainly by the severe environmental impacts and high carbon footprint of OPC production, as well as the rapid depletion of natural river sand. To mitigate these issues, researchers have developed sustainable concrete by incorporating industrial by-products, agricultural waste, and other alternative resources into conventional OPC. Hybrid concrete has attracted significant attention because it leverages the synergistic effects of multiple industrial by-products. Mixing more than one replacement into cement-based composites can provide different benefits at various loading stages, enhance concrete performance, and prevent severe defects (Ali et al., 2022). While the individual and binary applications of these industrial by-products are well-documented, their integration into highly complex, multi-component hybrid matrices remains underexplored.

Previous studies have shown that combining different industrial by-products yields superior strength and durability. For instance, ground granulated blast-furnace slag (GGBS) is a steel industrial by-product rich in active silica and alumina, at up to 40% and 24%, respectively (Xu et al., 2026). When mixed with cement,

GGBS reacts with calcium hydroxide ($\text{Ca}(\text{OH})_2$) to produce secondary hydration products of CASH, which improve the pore structure of the hardened paste. The reaction can be interpreted as $x\text{CaOH}_2 + y\text{SiO}_2 + z\text{Al}_2\text{O}_3 + m\text{H}_2\text{O} \rightarrow \text{C}_x\text{A}_y\text{S}_z\text{H}_m$ (gel) (Jalal & Srivastava, 2025). This secondary hydration significantly improves the long-term mechanical and durability properties of concrete. However, while high-volume GGBS replacement effectively reduces carbon emissions and improves long-term durability, it often delays early-age strength development. This necessitates using highly reactive GGBS with high-surface-area pozzolans to accelerate early-age pozzolanic reactions and densify the microstructural matrix. RHA is a silica-rich source and can accelerate pozzolanic reactions; however, increasing its replacement in the cement binder system hindered continuous improvement due to the dilution effect, which affects strength and durability performance.

Meanwhile, metakaolin (MK) is a thermally calcined product derived from kaolinitic clay at high temperatures, which contains high amounts of SiO_2 and Al_2O_3 . Mohamed and Tayeh (2024) mentioned that the calcination temperature of MK significantly influences the pozzolanic activity of binder materials. According to Allaoui et al. (2022), the crystalline kaolinite structure becomes increasingly amorphous as temperature increases from 500 to 900 °C, indicating that reactive aluminosilicates develop through the dehydroxylation transition process. In the present study, the highly pozzolanic reactivity of MK peaked at 750 °C, showing that the abundance of SiO_2 and Al_2O_3 in MK consumes more calcium hydroxide (CH) during cement hydration. However, producing MK requires energy-intensive thermal activation, and its properties depend strongly on calcination temperature and duration. Insufficient calcination may result in incomplete dehydroxylation and lower pozzolanic reactivity, whereas excessive thermal treatment can lead to recrystallization and the formation of relatively inert crystalline phases, consequently reducing its reactive amorphous fraction (Geu et al., 2025).

Consequently, binary replacement of GGBS, RHA, or MK could not adequately meet all requirements for sustainable cementitious composite materials, as improvements in one property may be offset by limitations in another. This indicates the need for a multi-component approach that uses materials with different reaction mechanisms or properties to achieve more balanced performance. In fact, reactions between binder materials, aggregates, and natural fibres can offer potential benefits in concrete applications. Finely ground quarry dust sand could improve particle packing and matrix densification, while coconut fibre can provide complementary physical properties through crack bridging and crack restriction. Nevertheless, their combined influence on concrete performance remains insufficiently understood. Furthermore, limited information compares the performance of different sustainable concrete mixtures in balancing compressive strength and water absorption. Thus, understanding how material combinations affect physical performance can help identify suitable sustainable concrete mixtures and promote the use of industrial and agricultural waste materials in construction.

MATERIALS AND METHODS

Materials

In this study, eight specimen mixtures were prepared, as shown in Table 1. All the specimens were prepared by blending Ordinary Portland cement (OPC) with multiple industrial wastes at designated replacement levels. The OPC and Rice Husk Ash (RHA) percentages were fixed at 60% and 10%, respectively, while Ground granulated blast-furnace slag (GGBS) and metakaolin (MK) were partially included at 30% of the cement weight. OPC used in this study conforms to MS EN 197:1 2014 CEM II/8-L 32.5N, whereas GGBS were obtained from YTL Cement Sdn Bhd and complies with BS EN 197-1. A local mill in Shah Alam, Selangor supplied the RHA and metakaolin (MK) used in this study. The rice husk was burned at 550°C to produce RHA, while the metakaolin was calcined at 700°C to enhance its pozzolanic reactivity. Then, the as-received RHA and metakaolin were sieved to pass a 150 µm sieve before incorporation into the cementitious binder. The fine aggregates used were locally quarried dust, prepared to pass through 1.18mm and 425 µm sieves. Coarse aggregates were crushed gravel with a maximum size of 14 mm. In this study, locally available coconut fibers were used with a nominal length of 30 mm, and a diameter ranging from 0.5 to 1.0 mm. The polycarboxylate-based superplasticisers were used at 1.5% to enhance the workability of the hybrid concrete mixtures, and the water-to-binder ratios (w/b) were maintained at 0.35 for all mixtures.

Methods

Compressive strength of the mixture was determined in accordance with ASTM C 39/ C39 M-10 and conducted on standard cubes of 100 x 100 x 100 mm. The water absorption test was carried out in accordance with ASTM C642-97. The prisms with dimensions of 100 x 100 x 500 mm were cut and cored to obtain cylinder samples with a diameter of 55 mm and a thickness of 40 mm. All mixes were tested at 7, 14, 21, and 28 days of curing.

Table 1. Mix design ratio of Hybrid Concrete

Mixture	OPC (%)	GGBS (%)	RHA (%)	MK (%)	Sand	Gravel	Coconut Fiber (%)	SP (%)	W/C ratio
G1	60	30	10	-	1.18mm	14mm	-	1.5	0.35
G2	60	30	10	-	425 μ m	14mm	-	1.5	0.35
M1	60	-	10	30	1.18mm	14mm	-	1.5	0.35
M2	60	-	10	30	425 μ m	14mm	-	1.5	0.35
G3	60	30	10	-	1.18mm	14mm	1	1.5	0.35
G4	60	30	10	-	425 μ m	14mm	1	1.5	0.35
M3	60	-	10	30	1.18mm	14mm	1	1.5	0.35
M4	60	-	10	30	425 μ m	14mm	1	1.5	0.35

RESULTS AND DISCUSSION

Several factors influence the compressive strength performance of hybrid concrete, including the pozzolanic reaction, SCM replacement level, and material size. As illustrated in Figure 1, the results demonstrate the effects of different sizes of quarry dust (1.18 mm and 425 μ m), with or without 1% coconut fiber, on the strength performance of the hybrid concrete containing 30% GGBS and 10% RHA by weight of cement replacement at 3, 7, 21, and 28 days of curing. The control mixture, containing neither quarry dust nor additional coconut fiber, showed the highest compressive strength at all curing ages. Including coconut fiber in both quarry dust sizes in hybrid concrete mixes shows a progressive reduction in strength performance, especially at early ages. Hybrid concrete with 1.18 mm quarry sand without coconut fibre showed a consistent increase in compressive strength, reaching 49.1 MPa, 59.5 MPa, 65.0 MPa, and 69.6 MPa at 3, 7, 21, and 28 days of curing, respectively. As the sand fineness was reduced to 425 μ m, the compressive strength of hybrid concrete containing 30% GGBS and 10% RHA as cement replacement improved with increasing curing age, except for a slight drop at 14 days of curing, with a 16% reduction from an earlier age.

In coconut fibre-dominant mixes, the compressive strength of hybrid concrete containing both quarry dust sizes (1.18 mm and 425 μ m) decreased significantly at all curing ages compared to control mixes. For example, at 7 days of curing, the inclusion of 1% coconut fiber in mixes containing 1.18 mm and 425 μ m quarry dust sand yielded 47.7 MPa and 43.3 MPa, compared with 49.1 MPa and 67.5 MPa for the control mix. A similar pattern was observed at 28 days of curing, with significant reductions of 11% and 12% for mixes containing 1.18 mm and 425 μ m quarry dust sand, respectively, compared with the control hybrid concrete. Technically, this behaviour stems from coconut fibre's hydrophilic nature and rough texture, which could absorb more water, increase internal friction, and reduce strength (Ali et al., 2012). Despite coconut fiber's tendency to reduce the strength of hybrid concrete, the inclusion of 30% GGBS and 10% RHA as cement replacement also mitigated this effect. Some scholars agreed that steel slag's hydraulic activity is much slower

than OPC's because slag contains lower levels of the main cementitious compounds (C_2S and C_3S) than cement (Zhao et al., 2017).

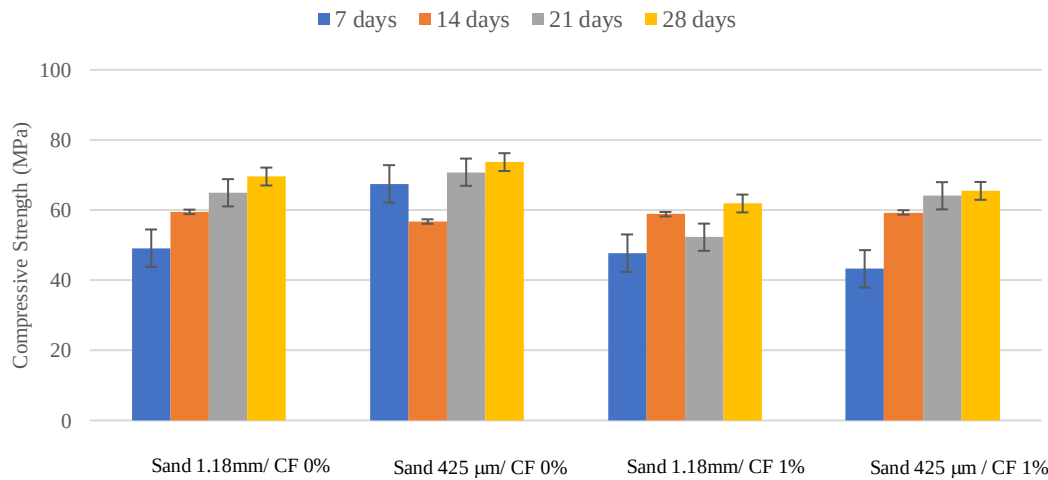


Figure 1: Compressive strength of hybrid concrete containing 30% GGBS and 10% RHA as cement replacement, containing 1.18mm and 425 µm quarry dust sand

Figure 2 indicates a hybrid concrete containing 30% MK and 10% RHA as cement replacement for mixes containing 1.18 mm and 425 µm quarry dust sand, with and without coconut fibre addition. Overall compressive strength results indicate that MK-based hybrid concrete improves significantly with coconut fibre addition and with increasing curing age, compared with the control mix. For example, a control hybrid concrete mix containing MK-RHA with 425 µm quarry dust sand shows strengths of 15.08 MPa, 14.2 MPa, 17.08 MPa, and 27.12 MPa at 7, 14, 21, and 28 days, respectively. Strength decreased noticeably at 14 days of curing, with a 6% reduction corresponding to 7 days of curing. This significant drop was due to dilution in the MK-RHA binder system, which had less available OPC to produce primary CSH and $Ca(OH)_2$ during secondary hydration. Similar results were also reported by Jamilu et al. (2023), indicating that replacing MK and RHA combined by more than 40% can reduce early-age strength performance. Including 1% coconut fibre with 1.18 mm quarry dust sand replacement in MK-RHA-based hybrid concrete gives the highest compressive strength. The increment observed is due to the improvement in the pozzolanic reaction of the aggregate-MK-RHA paste bond and also the coconut fiber's ability to improve the ductility and delay crack formation as the curing age increases (Akbar et al., 2025).

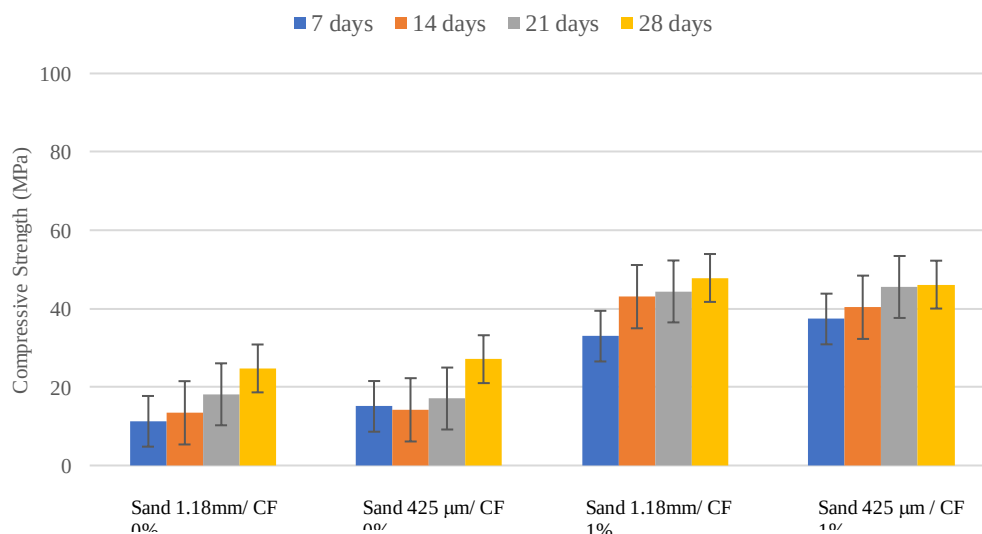


Figure 2: Compressive strength of hybrid concrete containing 30% MK and 10% RHA as cement replacement, containing 1.18mm and 425 µm quarry dust sand

Figure 3 shows the water absorption of hybrid concrete containing 30% GGBS and 10% RHA as cement replacement, with 1.18 mm and 425 μ m quarry dust sand. The results show some inconsistent trends for the 1.18 mm sand mixture with or without coconut fibre. For example, the water absorption rate of hybrid concrete containing 1.18 mm without fibre is 1.8% and 1.73% at 7 and 14 days of curing, respectively, before it significantly increases to 2.88% at 21 days of curing. This increase was due to the slow continuation of the pozzolanic reaction, which is linked to OPC hydration. However, the water absorption rate drops to 1.49% at 28 days of curing, indicating that the capillary pores in RHA-based hybrid concrete improved at later ages due to filler effects. At this stage, the improvement also resulted from the chemical reactivity and physical compatibility of RHA with slag in concrete (Geu et al., 2025).

In GGBS-RHA hybrid concrete containing 425 μ m quarry dust sand, the water absorption rate decreased consistently. For example, the water absorption rate reduced by almost 70% at 28 days compared to 7 days of curing age without any additional fiber and by approximately 42% in the mixture containing 1% coconut fiber. This reduction is attributed to the combined filler and pozzolanic effects of RHA, in which fine RHA particles promote particle packing while reactive silica consumes CH to form additional CSH gel, significantly refining the pore structure and reducing pore connectivity (Montazeri et al., 2025). In addition, a finer sand replacement size of 425 μ m may further enhance particle packing within the matrix, as the finer material acts as a filler as curing age increases. However, when coconut fibre is included, the water absorption rate decreases slowly due to the hydrophilic behaviour of coconut fibre (Akbar et al., 2025; Bediako et al., 2025).

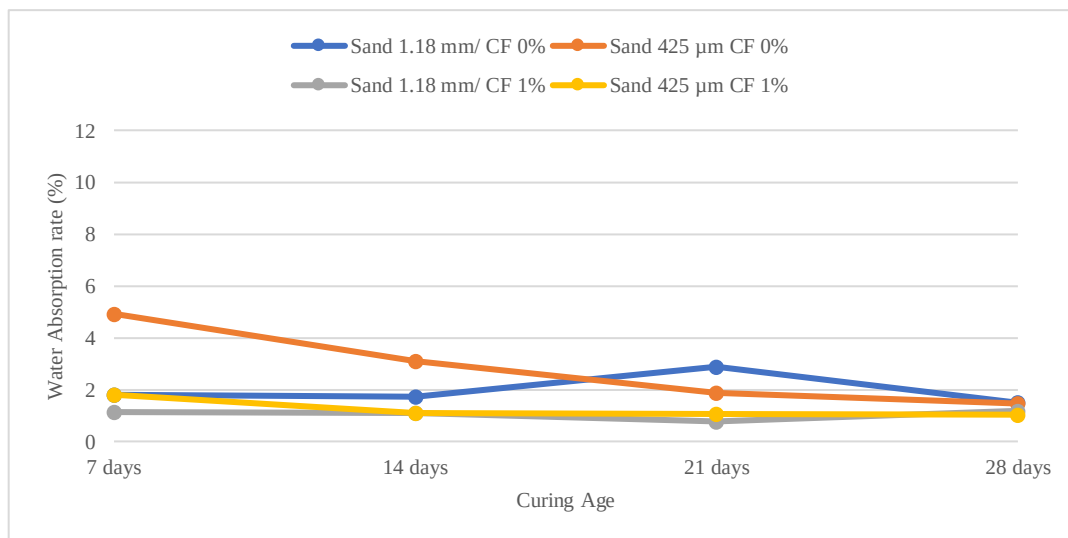


Figure 3: Water absorption of hybrid concrete containing 30% GGBS and 10% RHA as cement replacement, containing 1.18mm and 425 μ m quarry dust sand

In conjunction with the MK-RHA binder, different results were reported for blended mixtures containing 1.18 mm quarry sand, with or without coconut fibre. Without coconut fibre, the MK-RHA blended binder gives the highest water absorption rate among all the mixes. The water absorption rate is highest, at 9%, 8.2%, 5.8%, and 3.9% at 7, 14, 21, and 28 days of curing, respectively, as illustrated in Figure 4. The inclusion of coconut fiber gives a similar trend: as the curing age increases, the water absorption rate decreases. The behaviour proves that MK improves water absorption capacity at high replacement ratios. This improved performance can be attributed to MK's pozzolanic reaction during prolonged curing, which promotes additional hydration products and refines the pore structure, resulting in a denser yet less permeable matrix (Mohamed & Tayeh, 2024). The combination of RHA and MK creates a denser, less porous structure, which is critical for reducing water absorption. The synergy between these elements produces a matrix that is both extremely impermeable and robust, which is necessary for the long-term performance of concrete (Ahmad et al., 2021).

Incorporating 425 μ m fine quarry sand dust with or without fiber into the MK-RHA blended hybrid concrete system yields inconsistent water absorption rates at early and later ages. Figure 4 shows that the early-age water absorption rate for the sample without coconut fiber is 5.3%, while the sample with 1% coconut fiber is 4.41% at 7 days of curing. Both samples show fluctuating values at 14 and 21 days of curing, respectively,

indicating that pore-structure development and refinement remained inconsistent during the early curing period. This behaviour may be associated with the high fineness and water demand of MK and RHA, which can affect moisture availability, particle packing, and capillary pore development within the cementitious matrix. An early study by Fapohunda et al. (2017) reported that RHA can initially influence the hydration reaction due to its porous nature, which could absorb available mixing water, while continued pozzolanic reaction at later ages promotes pore refinement. However, as curing age increased, the reduction in water absorption rate was due to the continuous pozzolanic reaction, whereby reactive SiO_2 and Al_2O_3 from RHA and MK consume CH and produce additional CSH and CASH phases, significantly reducing pore connectivity and densifying the cementitious matrix (Endale et al., 2022; Gill & Siddique, 2018).

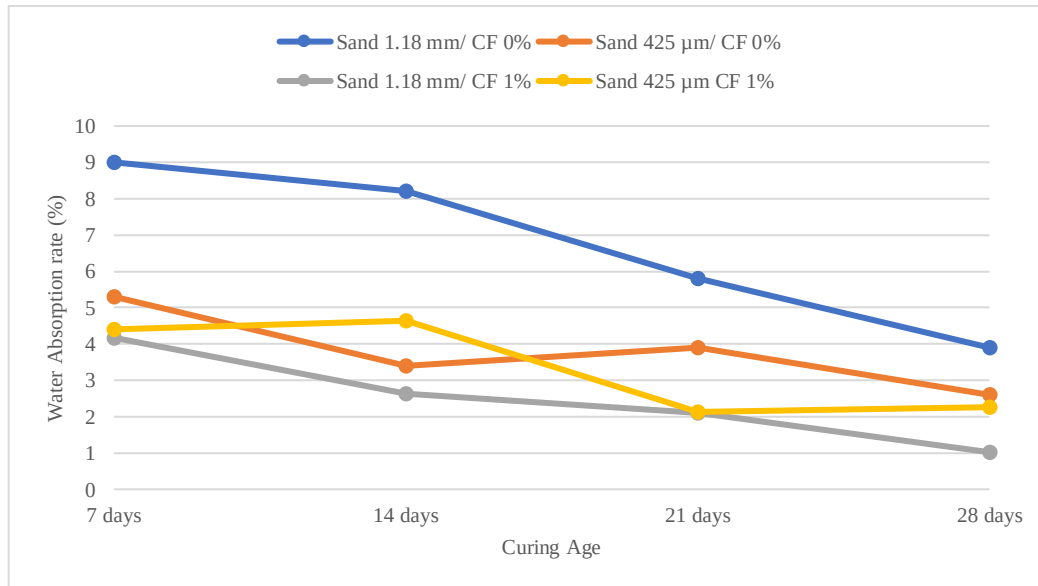


Figure 4: Water absorption of hybrid concrete containing 30% MK and 10% RHA as cement replacement, containing 1.18mm and 425 µm quarry dust sand

CONCLUSIONS

This study explores the synergistic effects of waste materials from MK, GGBS, and RHA as cement replacements, quarry dust as a fine-aggregate replacement, and the inclusion of natural fibres (coconut fibres). The following key conclusions are drawn:

1. The compressive strength of the GGBS-RHA hybrid concrete with 1.18 mm quarry dust sand achieved the highest performance gains, while fiber-dominant hybrid concrete mixes with 425 µm quarry dust sand showed a consistent increase as curing age increased. For the MK-RHA blended hybrid concrete system, including 1% coconut fiber with 1.18 mm quarry dust size gave the optimum value relative to the control.
2. Fiber-rich GGBS-RHA blended mixes exhibited lower water absorption than the control mix, indicating improved durability for hybrid concrete containing both 1.18 mm and 425 µm quarry dust sand. This improvement is attributed to a refined microstructure from GGBS-RHA densification and effective coconut fiber-matrix bonding. Meanwhile, the water absorption rate showed an inconsistent pattern in hybrid concrete containing MK-RHA blended cement regardless of quarry sand size and coconut fibre addition. The relatively higher water absorption in some MK and RHA mixtures may reflect increased water demand and the development of interconnected capillary pores, particularly at higher replacement levels.
3. Despite the promising results, several limitations should be acknowledged. The proposed mechanisms of matrix densification, pore refinement, and fibre-matrix
4. interaction were interpreted from compressive strength and water absorption results. Without direct microstructural analysis, this mechanism cannot be conclusively verified.

- Overall, the findings show the potential of integrating GGBS, RHA, MK, quarry dust sand, and coconut fiber to develop sustainable hybrid concrete while balancing binder pozzolanic reactivity, particle packing, strength development, and water absorption performance. This study also emphasizes the need to advance the Sustainable Development Goals (SDGs) for responsible consumption and production.

Conflict of Interest

The authors declare that no competing financial interests or personal relationships exist that could have appeared to influence the work reported in this paper.

Financial Support

This study was not financially supported by any grant scheme.

ACKNOWLEDGEMENT

The authors wish to thank YTL Cement Sdn Bhd, Malaysia, for providing the GGBS. Special thanks also go to all staff members in the Faculty of Built Environment laboratory and the Institute for Infrastructure Engineering and Sustainable Management (IIESM) laboratory for their assistance in analysing and conducting the experimental tests.

Credit authorship contribution statement

Nuril Izzeaty Ishak: Writing – Original draft, Methodology, Investigation, Conceptualization.

Mohd Fadzil Arshad: Writing, Conceptualization, Validation & Supervision

Nurul Hana Mohamad Zaini: Review & Editing

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