JSMBE

JOURNAL OF STRUCTURAL MONITORING AND BUILT ENVIRONMENT
e-ISSN: 2821-3432

Vol. 6 No. 1 (2026) 78-84
https://publisher.uthm.edu.my/ojs/index.php/jsmbe

Study on Strength Development of Concrete Using Rice Husk Ash, Quarry Dust and Polypropylene Fibres

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DOI: https://doi.org/10.30880/jsmbe.2026.06.01.010

Article Info

Received: 27 April 2026
Accepted: 15 June 2026
Available online: 30 June 2026

Keywords

Rice husk ash, non-destructive test, destructive test

Abstract

River sand and cement consumption has increased because of Malaysia's rising demand for concrete production. This has a bad impact on the environment, such as a lot of mining and damage of river stability. This study aims to reduce these environmental issues by investigating the use of alternative materials in concrete mixtures. The study specifically investigates the use of rice husk ash (RHA) as a substitute for cement, quarry dust (QD) as a substitute for fine aggregate Polypropylene fibre (PPF) as an additive to enhance concrete properties. The objectives of this study are to evaluate the workability, density, water absorption, surface hardness and compressive strength of blended concrete mixes using RHA, QD and PPF. Additionally, the study aims to assess the strength performance of concrete with varying replacement levels of these materials and to determine the optimal blend of RHA, QD and PPF for the best concrete mix proportion. RHA replaces Ordinary Portland Cement (OPC) at varying percentage of 0%, 6%, 8%, 10% and 12%. QD will replacing fine aggregate at constant percentages of 20% and PPF will add with 1% of total concrete weight. All samples are expected to have a compressive strength of 30 MPa after 28 days. The Department of Environment's (DoE) concrete mix design method was used to prepare 36 samples and tests were performed to assess the samples' hardness, water absorption, compressive strength and workability. The results show that while adding RHA, QD and PPF decreased the concrete's workability, higher percentages of QD and PPF replacement increased the concrete's compressive strength.

1. Introduction

Concrete is vital for Malaysia's infrastructure, but its production drives severe environmental degradation. Annually, the industry consumes 9 billion tons of sand, 1 billion tons of water, and 1.5 billion tons of cement, depleting resources, eroding riverbeds, and lowering water tables [1]. Furthermore, cement production alone generates roughly 7% of global CO_2 emissions [2]. This ecological crisis underscores the urgent need for sustainable material alternatives that reduce resource consumption and habitat destruction [1].

RHA is an underutilized agricultural waste, with 130 million tons produced annually [3]. Due to its high silica content, RHA acts as an excellent pozzolanic cement replacement that enhances concrete strength, durability, and chemical resistance [3][4]. However, its high-water demand can reduce mix workability and flowability [3].

Moreover, utilizing RHA simultaneously solves agricultural waste disposal issues and mitigates cement production emissions.

QD is a stone-crushing by-product that yields millions of tons of underutilized waste each year [5]. Serving as a fine aggregate replacement, QD increases concrete density, strength, and durability while lowering permeability, thereby reducing river sand over-exploitation [5]. Although QD reduces workability, proper mix designs can optimize its performance as a river sand alternative [6]. However, its precise optimal proportions and exact effects on workability require deeper investigation [7].

PPF improves concrete tensile strength and crack resistance in high-stress environments like pavements and bridges, yet massive amounts of PP waste remain underutilized [8]. Integrating PPF prevents shrinkage cracks and repurposes plastic waste [9], though it can decrease workability and require mix design adjustments [10]. This study evaluates the synergistic impact of RHA, QD, and PPF to develop high-performance, sustainable concrete because research on their combined effects is limited.

2. Material Preparation and Testing

2.1 Material

The materials are divided into conventional and sustainable components. The conventional materials consist of Grade 42.5 OPC complying with BS EN 197-1 as the main binder, sand following BS EN 12620 as fine aggregate, and 20 mm coarse aggregate. The sustainable materials include RHA, QD, and PPF (see Figs. 1). In this mix design, QD replaces 20% of the sand by weight as a constant variable, while RHA replaces cement at different levels of 6%, 8%, 10%, and 12% after being passed through a 75 µm BS sieve. Additionally, PPF is added at a fixed rate of 1% for all concrete series, with full details shown in Table 1.

(a) (b) (c)

Fig. 1 *Sustainable material used in this study as (a) Rice husk ash; (b) Quarry dust; and (c) Polypropylene fiber*

Table 1 *Material proportion for each concrete mix design*

Material	Percentages used in this mixing			
RHA	6	8	10	12
QD	20	-	-	-
PPF	1	-	-	-

Mix designation	Cement kg/m³	RHA kg/m³	QD kg/m³	PF kg/m³	Sand kg/m³	Agg. kg/m³
100OPC+100Sand	390	-	-	-	625	1159
20QD+1PPF	390	-	125	29	500	1159
20QD+1PPF+6RHA	367	23	125	29	500	1159
20QD+1PPF+8RHA	359	31	125	29	500	1159
20QD+1PPF+10RHA	351	39	125	29	500	1159
20QD+1PPF+12RHA	343	47	125	29	500	1159

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2.2 Experimental

Concrete specimens integrated with RHA and QD as cement and sand replacements, alongside PPF reinforcement, were evaluated using the ultrasonic pulse velocity test based on BS EN 12504-4:2021, the rebound hammer test in accordance with BS 1881-202:1986, and the compressive strength test according to BS EN 12390-3:2019. All sample specimens have standard dimensions of 100 × 100 × 100 mm and were subjected to testing after curing periods of 7 and 28 days.

3. Results and Discussion

3.1 Workability

The ease of handling and fluid consistency of the fresh concrete mixtures were assessed using the standard slump test conducted in compliance with BS EN 12350-2. The recorded slump values, which illustrate how the integration of RHA, QD, and PPF affects the workability of the fresh mix as illustrated in Figure 2. Based on the experimental observations, a progressive decline in workability was detected as the substitution levels of the eco-materials increased. The control mix (M1) achieved the highest slump value of 78 mm, while the inclusion of alternative materials caused the slump to drop steadily to 67 mm for M2, 63 mm for M3, 59 mm for M4, 56 mm for M5, and reaching a minimum of 54 mm for the highest replacement mix (M6).

This consistent loss in fluidity is primarily driven by the physical traits of the alternative components; the highly porous structure of RHA particles naturally demands more mixing water, and the sharp, angular geometry of crushed QD intensifies internal mechanical friction within the paste. Furthermore, the addition of PPF creates a physical, three-dimensional network filament structure that mechanically blocks and restrains the free flow of the concrete mix. To counteract this combined stiffening effect and ensure the concrete remained placement-ready without altering the target water-cement ratio, a chemical admixture known as a superplasticizer (SP) was introduced. Acting as a water-reducing agent, the SP was selectively incorporated into the dryer, high-replacement design mixes (M3 to M6) to successfully recover their flowability and uniform consistency.

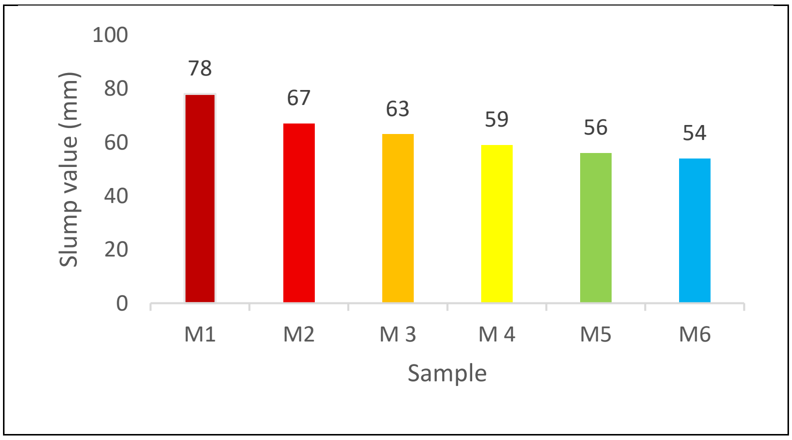

Fig. 2 *Slump test results*

3.2 Rebound Hammer Test

Assessment of concrete surface hardness was carried out using the rebound hammer test across four (4) different structural surfaces per specimen. Evaluated in accordance with BS EN 12504-2:2021, the resulting 7-day and 28-day rebound number (RN) data trends are graphically illustrated in Fig. 3. During the initial 7-day phase, the experimental results revealed a distinctive decline in surface hardness as alternative materials were incorporated. The control mix (M1) achieved a rebound value of 27.25 (Fair), whereas the modified mixes exhibited lower values, dropping from 25.00 (Fair) for M2 and 20.15 (Fair) for M3, down to "Poor" quality ratings of 19.75 for M4, 19.30 for M5, and a minimum of 18.80 for M6. This initial lag is primarily attributed to the delayed pozzolanic reaction of RHA and the non-reactive nature of the PPF filaments at the outer layer.

However, by the 28-day mark, a noticeable recovery and stabilization in surface hardness were observed across almost all configurations. The control mix (M1) reached a peak value of 38.50 (Good), while the eco-concrete mixes successfully advanced into the "Good" quality rating range, yielding rebound numbers of 33.25 for M2, 32.75 for M3, 33.50 for the optimum M4 mix, and 31.45 for M5. Conversely, the high-replacement mix M6 experienced a drop back to a "Fair" rating with an RN of 27.65. This late-stage hardness in the optimum designs is fuelled by the pozzolanic reaction between the amorphous silica in RHA and calcium hydroxide by-products to generate a denser microstructural matrix, while the fine QD particles acted as an efficient micro-filler to close up surface voids.

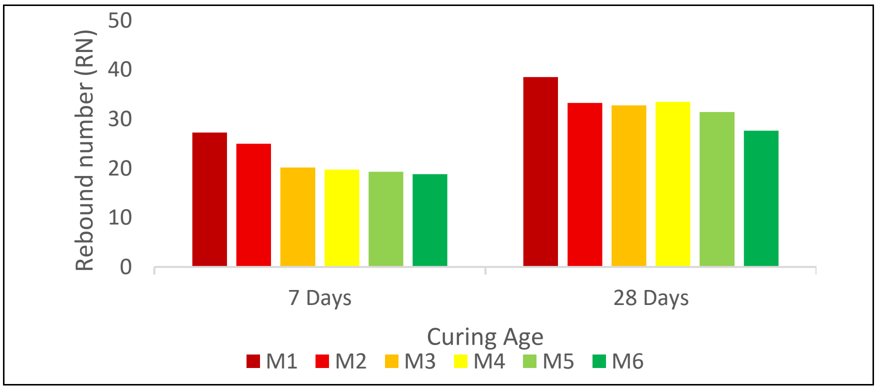

Fig. 3 *Rebound hammer result*

3.3 Ultrasonic Pulse Velocity (UPV)

The internal homogeneity and structural soundness of the 100 mm concrete cube specimens were evaluated using UPV testing in compliance with BS EN 12504-4:2021, where longitudinal pulse velocities exceeding 4.5 km/s indicate an "excellent", while readings between 3.5 km/s and 4.5 km/s represent "good" quality concrete. The recorded 7-day and 28-day UPV data trends across the different material configurations are plotted in Fig. 4. During the initial 7-day testing phase, the control mix (M1) achieved a velocity of 4.11 km/s, while the modified eco-concrete series exhibited slightly lower, yet stable velocity readings of 3.85 km/s for M2, 3.82 km/s for M3, 3.84 km/s for M4, 3.81 km/s for M5, and 3.80 km/s for M6, confirming that proper compaction prevented major internal voids despite the introduction of alternative materials.

Over the 28-day curing period, the velocity values experienced a progressive upward shift across all configurations as the control mix (M1) advanced into the "excellent" threshold at 4.65 km/s. Concurrently, the sustainable concrete mixes firmly established themselves within the high-end "good" quality range, yielding velocity values of 4.38 km/s for M2, 4.32 km/s for M3, 4.35 km/s for the optimum M4 mix, 4.33 km/s for M5, and 4.32 km/s for M6. This positive velocity phenomenon is directly linked to the progressive dense filling of internal capillaries by the secondary calcium silicate hydrate (C-S-H) gels produced through RHA's pozzolanic activity, working in tandem with the physical micro-filling capability of the fine quarry dust particles.

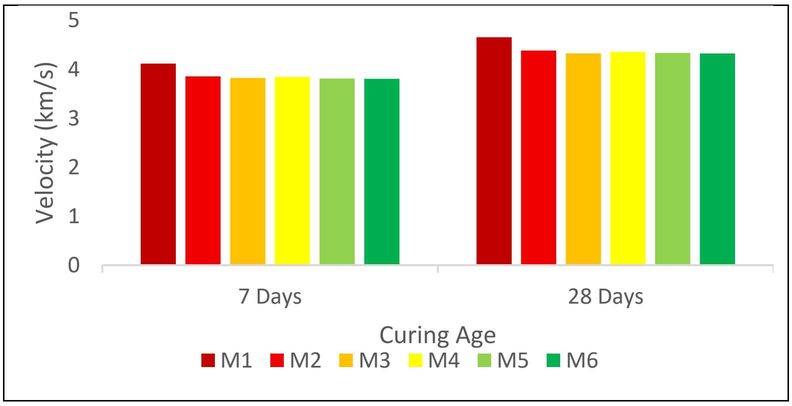

Fig. 4 *Ultrasonic velocity result*

3.4 Compressive Strength

The physical performance and load-bearing capacity of the modified concrete series were evaluated through destructive compressive strength testing in accordance with BS EN 12390-3:2019. Heavy-duty hydraulic compression machines were utilized to apply a continuous, uniform axial load onto the 100 mm cube specimens until structural failure occurred, allowing for the precise calculation of maximum compressive stress. To meet standard structural engineering criteria, the mixes were targeted against a minimum design strength threshold of 30 MPa.

The structural evolution profiles capturing the compressive strength development at the critical 7-day and 28-day water curing milestones are illustrated in Fig. 5. The experimental data revealed a distinctive strength development curve influenced by the dual action of the alternative materials and synthetic reinforcement. In the early 7-day testing phase, the control mix (M1) achieved a strength of 30.2 MPa, whereas all eco-concrete mixes displayed a noticeable strength deficit, dropping from 25.30 MPa for M2 (0% RHA) down to 23.80 MPa (M3), 22.80 MPa (M4), 20.50 MPa (M5), and a minimum of 19.60 MPa for M6 (12% RHA). This initial lag is driven by the sluggish, time-dependent nature of the pozzolanic reaction in RHA.

However, at the 28-day mark, a highly progressive strength recovery was observed across all configurations. The control mix (M1) reached a peak value of 40.30 MPa, while the modified mixes successfully surpassed the 30 MPa structural target, yielding strengths of 37.29 MPa for M2, 36.50 MPa for M3, 34.28 MPa for M5, and 30.79 MPa for M6. Notably, the optimum sustainable mix, M4 (containing 8% RHA), demonstrated a strength rebound up to 37.40 MPa, eclipsing the performance of the lower-percentage RHA mix (M3). This substantial late-stage strength enhancement is attributed to the chemical synergy where amorphous silica from RHA interacts with calcium hydroxide to form secondary Calcium Silicate Hydrate (C-S-H) gels, dense interlocking micro-filler action from the 20% fine QD particles, and the crack-bridging mechanics provided by the 1% multi-directional PPF matrix. Beyond the 8% RHA threshold (M5 and M6), the strength began to decline due to an excess of unreacted silica particles acting as internal weak points.

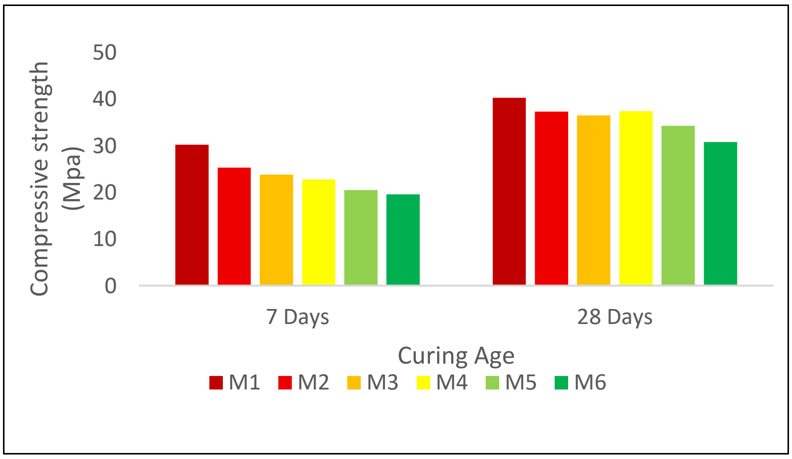

Fig. 5 *Compressive strength test results*

4. Conclusion

The results of this study effectively proved the research objectives, producing important conclusions that directly addressed each objective. The fresh state properties evaluation successfully determined the impact of the eco materials on concrete consistency, where the integration of alternative materials led to a progressive decline in slump values from 78 millimetres for the control mix down to a minimum of 54 millimetres for mix M6. This fluid loss is governed by the internal friction of angular quarry dust, the high water absorption of porous rice husk ash, and the physical flow restraint from the polypropylene fibre filaments, but all modified designs successfully retained their fresh state stability within the target medium workability zone of 54 millimetres to 67 millimetres, ensuring sound handling without segregation. Non-destructive rebound Hammer testing effectively mapped the surface quality development of the specimens. The modified mixes initially exhibited a hardness deficit at 7 days with values dropping as low as 18.80 because of the slow early stage pozzolanic kinetics of rice husk ash, but a substantial microstructural recovery was recorded at 28 days, prompting mixes M1 through M5 to advance into the good structural category. Mix M4 achieved the optimal rebound number of 33.50, verifying that the weak calcium hydroxide crystals were chemically transformed into dense void filling secondary calcium silicate hydrate gels.

The UPV monitoring verified excellent internal homogeneity across all concrete matrix configurations. All modified specimens safely secured a good quality rating at 28 days with velocities tightly clustered between 4.32 kilometres per second and 4.38 kilometres per second, proving that the multi material replacement did not compromise internal core density because the wave scattering at synthetic fiber boundaries was completely offset by the combined micro filling efficiency of fine quarry dust packing and pozzolanic rice husk ash crystallization. The destructive testing successfully validated the structural capacity of the eco concrete, with every altered design mix comfortably surpassing the industrial design threshold of 30 MPa at 28 days. Mix M4 comprising 20 quarry dust, 1 polypropylene fibre, and 8 rice husk ash was established as the optimum mix configuration, producing a premium compressive strength of 37.40 MPa and an excellent durability rating through a minimized water absorption of 2.85. This performance highlights a peak physical chemical synergy between the crack bridging polypropylene fibre network, the pore blocking rice husk ash microstructure, and the dense particulate aggregate packing of quarry dust, proving that quality structural concrete can be effectively constructed from industrial and agricultural byproducts without compromising engineering performance.

Future investigations can implement several critical refinements to expand the academic scope and maximize the chemical efficiency of this composite sustainable concrete.

- Optimization of the dosage of high range water reducing superplasticizers in rice husk ash and quarry dust matrices can restore target flowability without altering the water cement ratio.
- Comparative studies should investigate the structural effects of substituting fine aggregates with other local industrial or agricultural byproducts such as spent garnet or oil palm shell fine aggregates.
- Long term mechanical evaluations at 56, 90, and 180 days are necessary to fully capture the late-stage strength contributions of the slow reacting rice husk ash pozzolan.
- Advanced chemical and microstructural characterizations including Scanning Electron Microscopy, X ray Diffraction, and X ray Fluorescence will allow researchers to analyse interfacial transition zones and chemical bonding.
- Implementation of a strict dry mixing sequence for aggregates, quarry dust, and polypropylene fibres prior to water introduction is essential to eliminate fibre balling and guarantee uniform matrix dispersion.
- Future experimental frameworks must subject the composite concrete to rigorous long term durability testing including water permeability, acid attack, and accelerated carbonation resistance tests.

Acknowledgement

Praise to Allah, the Most Gracious and Merciful, for granting the strength, wisdom, and opportunity to successfully complete this study. Deepest gratitude is extended to my supervisor, Prof. Madya Ir. Ts. Dr. Abdul Halim Bin Abdul Ghani, for his invaluable guidance, constant encouragement, and profound expertise throughout this project. Heartfelt thanks go to my family for their continuous love, patience, sacrifices, and essential emotional and financial support. Sincere appreciation is also shared with my friends and colleagues for their motivation and companionship, as well as everyone who directly or indirectly contributed to bringing this project to completion.

Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design****: Che Mohamad Redhwan Che Hamzah;* ***data collection****: Che Mohamad Redhwan Che Hamzah;* ***analysis and interpretation of results:*** *Che Mohamad Redhwan Che Hamzah, Abdul Halim Abdul Ghani;* ***draft manuscript preparation****: Che Mohamad Redhwan Che Hamzah. All authors reviewed the results and approved the final version of the manuscript.*

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