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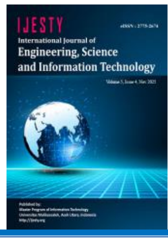

Effects of Curing Conditions and Combined Pozzolanic Material on Compressive Strength of Reactive Powder Concrete

Said Jalalul Akbar, Yulius Rief Alkhaly*, Maizuar, M Ibnu H F Harahap

Department of Civil Engineering Department, Faculty of Engineering, Universitas Malikussaleh, Aceh, Indonesia

**Corresponding author E-mail: yr.alkhaly@unimal.ac.id*

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Abstract

Reactive Powder Concrete (RPC) is a type of concrete with an extremely dense matrix and high compressive strength. The compressive strength of RPC was examined in this study to evaluate the effects of the combination of silica fume (SF) and rice husk ash (RHA) with up to 50% by weight of cement, which provided the highest compressive strength and low cement content under normal curing and steam curing methods. The results showed that the combination of 5% SF or 10% SF with 25% - 45% RHA reaches compressive strength over 100 MPa at the age of 28 days with a low cement content of about 650 kg/m3 under both curing conditions and maintains the slump flow more than 200 mm. This study demonstrates that SF and RHA can be used up to 50% by weight of cement to produce RPC with a compressive strength of over 100 MPa.

Keywords: *Reactive Powder Concrete, Silica Fume, Rice Husk Ash, Compressive Strength, Normal and Steam Curing.*

1.Introduction

Reactive Powder Concrete (RPC) is a type of concrete that has an ultra-dense matrix made possible by a packing density method that reduces the voids between the constituent material particles [1] . Richard and Cheyrezy at the Bouyques Laboratory, Lafarge Group, France, developed RPC for the first time in the early 1990s. RPC has several benefits, including extremely high compressive strength, ductility, and durability [2]. Due to the absence of coarse aggregate, RPC mixes differ from conventional concrete. The material's largest permitted particulate size is 800 µm. Silica fume (SF), quartz sand, quartz powder, Portland cement, and superplasticizer (SP) are the typical constituents in RPC mixtures. RPC is classified as part of ultra high performance concrete (UHPC), and it has a compressive strength of up to 800 MPa [1].

In the concrete mixes, the inclusion of ultra-fine silica fume (SF) with a high amorphous silica content plays a vital role in imparting essential physical characteristics such as filling and lubricating properties, as well as contributing to pozzolanic effects that enhance both the compressive strength and durability [3]. Therefore, it is necessary to investigate substitute materials that can successfully replace SF while providing equivalent functions and advantages, given its importance to the overall performance of concrete [4].

Rice husk ash (RHA) presents a promising replacement for silica fume (SF) due to its availability and composition. The production of RHA is obtained from the burning of rice husks, which accounts for one-fifth of the world's annual rice production of 690 million metric tons, and may provide a potential solution [5], [6]. Controlled burning of rice husks produces RHA, which typically contains 90-96% amorphous silica. Its physical characteristics include an average particle size between 0.15 - 0.25 µm and a very high specific surface area above 220 m^2/kg [7]. Hence, RHA has physical properties that meet the criteria as an SF replacement [8].

Jamil et al., (2016) investigated the ability of RHA to partially replace cement in concrete mixtures. Their analysis focused on the chemical contribution of RHA, determining a theoretical replacement level of 14.3% for ASTM type-I cement containing 55% C3S and 19% C2S. This result was derived based on a chemical reaction model that occurs during cement hydration. Notably, their theoretical findings aligned well with experimental results reported in other research [9].

2. Literature Review

2.1. Utilization of rice husk ash in concrete production

Faried et al. (2021) examined the effects of various nano-rice husk ash (NRHA) types on the mechanical properties, ultrasonic pulse velocity, and durability of UHPC. They produced four types of NRHA by calcining rice husk at different temperatures (300, 500, 700, and 900 °C) for a constant duration of 3 hours. NRHA produced at 900 °C with a 1% replacement ratio achieved the highest compressive strength at both 7 and 28 days. However, for the 28-day strength (around 23.9 MPa), a 3% replacement ratio of NRHA calcined at 700 °C proved more effective. This addition also led to a 20% increase in splitting strength (reaching 23.9 MPa) and a 57% increase in flexural strength. Overall, a 3% replacement with NRHA calcined at 700 °C yielded the best mechanical performance and enhanced concrete durability. While the ultrasonic pulse velocity test indicated a homogeneous concrete structure, scanning electron microscope (SEM) images revealed that NRHA incorporation might promote the formation of micro-cracks and voids [5].

In 2021, Zhang et al. developed a new generation of high-performance engineered cementitious composites (ECCs) by partially replacing cement with RHA at a rate of up to 40%. Surprisingly, despite the reduction in cement content, the compressive strength of these RHA-ECCs increased. Compared to the control mix (M-C) with a strength of 80 MPa at 28 days, the RHA-ECC with the highest substitution level (M-25) achieved a strength of 111.3 MPa. This improvement is likely due to the combined effects of filler and pozzolanic reaction of RHA, as confirmed by XRD analysis. However, there was a trade-off at the microscopic level. The reduced cement content in RHA-ECCs may have led to insufficient hydration products around the fibers, weakening the frictional bond at the fiber-matrix interface compared to the control mix (M-C). This, in turn, resulted in a slight decrease in the ultimate fiber-bridging stress and consequently, the tensile strength of the ECCs. Despite this drawback, incorporating RHA as a cement replacement offers a significant environmental benefit. Life cycle assessment (LCA) results showed that using RHA in ECCs considerably reduces the environmental impact across all categories compared to the control specimens. This suggests that RHA-ECCs can be a sustainable alternative construction material while offering improved compressive strength [10].

Huang et al. (2017) reported the use of RHA as a partial replacement for SF in fresh UHPC mixtures. Their study revealed that RHA addition improved both the compressive strength and impermeability of UHPC. A replacement ratio of 2/3 SF with RHA yielded the most significant enhancement, with increases in compressive strength of 9.76%, 14.50%, and 10.02% at 3, 28, and 120 days, respectively. The research also examined the permeability of cylindrical UHPC specimens under different loading conditions. While vertical loading increased permeability, lateral loading had a negligible impact on water absorption and chloride ion penetration. Notably, when the loading level remained below 70% of the ultimate strength, UHPC samples containing RHA exhibited lower water absorption and chloride ion penetration than the control mix. These findings suggest that calcined RHA (heated at 500 °C) can effectively improve both the strength and permeability of UHPC, making it a promising sustainable alternative to SF in UHPC production [11].

Gill and Siddique (2017) found that the combined effects of RHA and metakaolin (MK) on the properties of self-compacting concrete (SCC). Their findings revealed significant improvements across various performance metrics. The addition of MK and RHA led to a substantial increase in compressive strength, with enhancements of 27%, 42%, and 48% observed at the ages of 28, 90, and 365 days, respectively, compared to the control mix. Additionally, the incorporation of these pozzolans resulted in a remarkable decrease in water absorption (45%) and porosity (46%). Resistance to sulphate attack was also significantly improved by the combined use of MK and RHA. When 10% each of MK and RHA were used together, the concrete experienced only a 4.8% loss of strength at 365 days, compared to a much higher loss of 17.9% in the control mix. XRD and SEM analyses further supported these observations, revealing a denser microstructure in the mixes containing MK and RHA. This denser structure suggests the formation of more calcium-silicate-hydrate (CSH) gel, a key binding phase that contributes to enhanced strength and durability [12] .

Alternatively, concrete compressive strength can also be achieved by post-curing or curing treatments as well as RPC [13]. Three types of treatment are available: the standard curing method, the heat curing method, and the steam curing method [14][15]. Dhundasi and Khadiranaikar (2019) described the influence of curing conditions on the mechanical properties of concrete, specifically compressive strength, split tensile strength, and flexural strength. They compared the effects of normal curing and a combined curing method. The combined curing method led to a significant increase in compressive strength of 30 N/mm² compared to normal curing, with the strengths reaching 163 N/mm² and 172 N/mm², respectively. Flexural strength was reported to be 25-30% of the concrete's compressive strength at the age of 28 days [16].

The research of Yazıcı et al., (2013) concluded that the compressive strength of RPC has been greatly influenced by autoclave time, pressure, and temperature. Higher temperatures and pressure accelerate the chemical reactions between cementitious materials in RPC. This, in turn, influences the composition of the hydration products that form during the curing process. It's also worth noting that incorporating SF and fibers is essential for RPC to achieve a compressive strength exceeding 200 MPa [17].

Given the aforementioned factors, there remains a restricted application of combinations involving high volumes of pozzolanic materials in RPC production. Employing a blend of pozzolanic materials holds the potential to alleviate environmental impacts by reducing the cement content within the RPC mixture [18].

2.2. SF-RHA combinations in the production of RPC

Despite its effectiveness in enhancing the pozzolanic reaction and packing density of granular materials in RPC, SF presents significant challenges for widespread adoption. Its high cost and limited availability are particularly problematic for the construction industry in developing countries [19]. According to studies by Van Tuan et al. (2011) and Alkhaly et al. (2022), RHA shows a promising replacement for SF. The results still showed satisfactory performance for the mechanical properties of RPC when both were added to the mix [20], [21].

Table 1. Comparison of RPC Mix Compositions Reported in the Previous Studies

Description		Van Tuan et al. (2011)	Alkhaly et al. (2022)
		10% SF + 10 % RHA	25% SF + 20% RHA
Composition (kg/m^3)	Cement	885.00	650.40
	Silica fume	88.50	162.60
	Rice Husk Ash	88.50	130.10
	Quartzite Powder	-	381.30
	Silica Sand	885.00	876.10
	Water	159.30	154.50
	Superplasticizer	10.62	19.50
Sample type & size (mm)	Cube	50.00	71.70
Compressive strength (MPa)	7 days	160.23	145.00
	28 days	180.70	148.70

Van Tuan et al. (2011) obtained RPC compressive strengths of 160.23 MPa after 7 days and 180.70 MPa after 28 days with cement replacement by SF and RHA at 10 wt%. The materials used were silica sand with an average particle size of 225 µm, Portland cement (CEM I 52.5N), RHA with a particle size of 3.6 µm and polycarboxylate based superplasticiser at doses ranging from 0.76 to 1.20% by weight of cement to achieve a constant slump flow of 210 mm to 230 mm. The samples were treated in a fog room until the testing day [20].

Meanwhile, Alkhaly et al. (2022), produced RPC compressive strengths of 145 MPa at 7 days and 148.70 MPa at 28 days by replacing cement with SF and RHA at 25% and 20% by weight of cement, respectively. The materials used were ordinary Portland cement, SF, and a polycarboxylate-based superplasticizer at a 2.4% dosage by weight of cement. This was done to achieve a slump flow ranging from 330 mm to 350 mm. Additionally, quartz sand graded of 150–600 µm, quartzite powder sized of 5–25 µm, and RHA with particles of 0.45–0.75 µm were included in the mixture. The treatment method used was a steam curing at 90 ^{O}C for 72 hours, and then the samples were immersed until the day of testing [21]. A comparison of the mix compositions of the two studies is shown in Table 1.

As seen in Table 1, Alkhaly's RPC has a reasonably high SF content with an RHA of 20% by cement weight, while Van Tuan's RPC mix still contains a significant proportion of cement and 10% RHA by weight. Based on these viewpoints, this research is carried out towards designing RPC mixes with a high RHA content and a low cement and SF content.

The purpose of this study is to investigate the effects of normal curing and steam curing, as well as combination pozzolanic materials of SF and RHA with up to 50% by weight of cement on the compressive strength of RPC.

3. Methods

3.1. Silica fume

Silica fume (SF), a by-product of the silicon ferro industry with a fine texture and grey color, has a diameter of 0.1 to 0.2 microns, about 1/100th the size of cement particles. It has been used to significantly improve the compressive strength and durability of concrete [22]. The enhancement of concrete properties involves reducing pore volume, improving rheological properties, and forming secondary CSH through the reaction between pozzolan and calcium hydroxide in the primary hydration process [23]. SF, owing to its pozzolanic and inert filler characteristics, effectively occupies the voids between the cement paste and aggregate [2].

SikaFume®, following ASTM C1240 standards, served as the primary supplementary cementitious material (SCM) in the RPC mix. The chemical compositions of the SF employed in this study are detailed in Table 2.

3.2. Rice husk ash

Rice husk ash (RHA) is produced by burning rice husks under ambient conditions. After calcining for 24 hours at temperatures between 600 and 800˚C, RHA has a silica (SiO_2) content of 90-95% [24]. RHA has been shown to have a high content of amorphous silica, which is essential for the pozzolanic reaction in concrete. This reaction contributes to the effectiveness of RHA as an additive [25]. Incorporating RHA into concrete mixes reduces thermal cracking and plastic shrinkage, while enhancing concrete strength, impermeability, and durability [26], [27].

Rice husks are burned at room temperature, and then the material is sieved through a No. 30 sieve (0.600 mm) to produce coarse ash. Next, the husks are pulverized and sieved through a No. 200 (0.075 microns) sieve. Finally, the resulting material was burned in a furnace at 700 ºC for 2 hours to obtain fine ash.

3.3. Cement

Portland cement is a precisely controlled chemical blend of calcium (Ca), silica (Si), aluminium (Al), and iron (Fe), along with minor additives like gypsum added during the final grinding to regulate concrete setting time. Type I and Type II cements, characterized as low alkali and low C_3A cements, are highly recommended for producing RPC, ensuring ultra-high-quality concrete [28].

For this study, Type I Portland cement (PC) produced by Semen Andalas, Indonesia, was chosen as the primary binder. This cement complies with ASTM C150 standards, ensuring consistent quality. The chemical composition of the cement is provided in Table 2.

3.4. Quartzite powder

Quartzite is a tough rock formed from sandstone through high pressure and heat. It's mostly quartz, but it can have small amounts of other minerals. This metamorphic rock comes from various sources like sandstone, siltstone, and even veins rich in quartz. The intense heat and pressure cause the quartz to recrystallize and fuse together, making quartzite a very strong and durable rock [29].

Quartzite rock, sourced from a local mountain in Aceh, Indonesia, was crushed into powder using the Los Angeles Abrasion Machine. The resulting material was then sieved through a No. 200 sieve to obtain a uniform particle size. Finally, the quartzite powder (QP) was calcined at a designed furnace temperature of 700 °C for 2 hours. [30]. Tables 2 show the chemical composition and physical properties of QP.

3.5. Quartz sand

A key ingredient in high-performance RPC is fine quartz sand (150-600 microns) [31]. This sand allows denser packing in the mix, resulting in much stronger (up to 200 MPa) and more durable concrete compared to conventional types of concrete [2]. Quartz sand (QS) with a maximum particle size of 602 microns, quarried in Aceh, Indonesia, was used as a filler.

3.6. Water and superplasticizer

Unlike normal concrete, RPC uses very fine particles and much less water. This low water content creates a dense structure with almost no porosity. Even though less water is used, it's still essential for a chemical reaction between water and cement that binds concrete materials together [32]. To obtain a better mix flow with less water, special chemicals called superplasticizers are typically added [2].

A superplasticizer serves as an admixture, a substance incorporated into the concrete mixture either before or during the mixing process to modify the concrete properties [33]. Reverse osmosis water is employed in the RPC mixture to safeguard it against water-soluble contaminants.

Sika® ViscoCrete®-8045 P, a modified polycarboxylate superplasticizer conforming to ASTM C 494, is utilized as a fluidizing agent to achieve the necessary workability.

Table 2. Chemical Composition of Materials

Property	Constituents (wt.%)				
	PC	RHA	SF	QP	QS
Na_2O	-	0.82	-	0.92	-
MgO	1.95	1.05	1.14	1.07	0.72
Al_2O_3	4.58	-	-	13.3	1.14
SiO_2	21.71	92.66	97.05	32.96	97.92
K_2O	-	-	1.81	1.88	-
CaO	71.76	1.3	-	36.01	0.22
FeO	-	-	-	12.13	-
LOI	-	4.20	-	1.76	-

3.7. Mixture composition

The mix of proportions was based on the previous studies [14]. Two types of pozzolanic materials, SF and RHA, were incorporated into the mixture in varying proportions.

As shown in Table 3, the mixtures were designated as M1 and M2. M1 contained 5% SF with RHA content ranging from 30% to 45% at 5% increments. M2 contained 10% SF with RHA content varying from 25% to 40% at 5% increments. In total, the pozzolan content in both mixtures ranged from 35% to 50%.

Table 3. Composition of Mixtures

Combination (SF+RHA)		5% SF				10% SF			
		30% RHA	35% RHA	40% RHA	45% RHA	30% RHA	35% RHA	40% RHA	45% RHA
Mixtures		M1-30	M1-35	M1-40	M1-45	M2-25	M2-30	M2-35	M2-40
Total Pozzolan (%)		35	40	45	50	35	40	45	50
Materials (kg/m^3)	PC	650.49	650.49	650.49	650.49	650.49	650.49	650.49	650.49
	RHA	195.15	227.67	260.20	292.72	162.62	195.15	227.67	260.20
	SF	32.52	32.52	32.52	32.52	65.05	65.05	65.05	65.05
	QS	1041.99	1000.81	959.64	918.46	1025.08	983.90	942.73	901.55
	QP	381.35	381.35	381.35	381.35	381.35	381.35	381.35	381.35
	Water	129.77	129.77	129.77	129.77	135.95	135.95	135.95	135.95
	SP	16.39	16.39	16.39	16.39	17.17	17.17	17.17	17.17

3.8. Mixing and slump flow test

Proper mixing is essential for achieving optimal performance in RPC [34]. A pan mixer with a capacity of 40 kg was used, and the following steps were taken for the preparation of the mixture (Fig. 1).

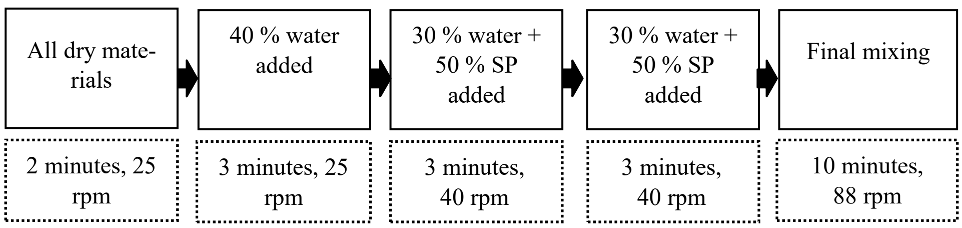

Fig 1. Mixing Processes

Following the mixing, workability of the fresh RPC was measured using the mini-cone slump flow test according to ASTM C 1437. This involved not compacting the mixture and keeping the table static during the test.

3.9. Curing and compressive strength

Two curing procedures were used to produce the RPC specimens:

Curing condition 1 (CC1): Normal or water immersion curing until 7 days and 28 days age at room temperature. Curing condition 2 (CC2): After one day of pouring, steam cure for three days at 90 ^{0}C, followed by standard curing at room temperature until 7 and 28 days of age.

RPC samples were tested for compressive strength on days 7 and 28. The compressive strength was determined by averaging the results of three 70.7 mm × 70.7 mm × 70.7 mm samples tested on an ELE ADR 1500 compression testing machine at a load rate of 3.5 kN/s.

4. Results and Discussion

4.1. Effects of combined pozzolanic material on slump flow

The slump flow tests revealed that variations in RHA and SF content impacted the slump flow diameter. In mixture M1 (5% SF), the diameter decreased with increasing RHA content. A similar trend was observed in M2 (10% SF), though M2 consistently displayed a larger slump diameter at all RHA levels. These findings suggest that increasing RHA content leads to a stiffer mix. The reason for this result is that RHA absorbs more water than SF [20].

Conversely, increasing the SF content from 5% to 10% led to a consistently higher slump flow diameter across all RHA levels. This signifies an enhanced workability of the mix, making it flow more readily. All mixtures in this study satisfied the minimum slump flow diameter of 200 mm specified by ASTM C 1437 for mortar. This indicates good workability, allowing for easy application.

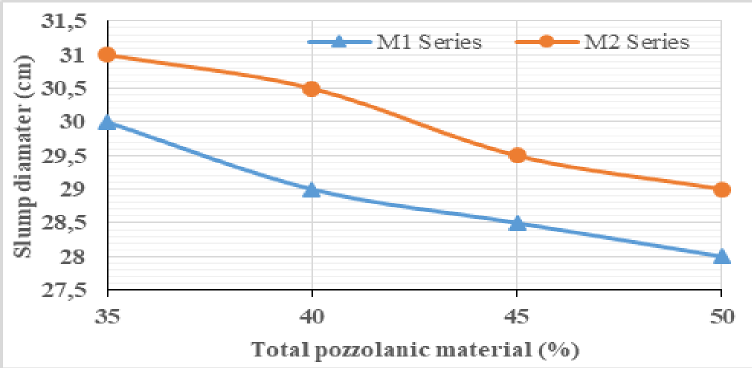

Fig 2. Slump Flow of M1 and M2 Mix Series

4.2. Effects of curing conditions on compressive strength

As shown in Fig. 3 and Fig. 4, CC2 exhibited consistently higher compressive strength than CC1 in all mix designs and pozzolan content variations. This enhanced performance can be attributed to the elevated temperature (90 °C) employed in CC2, which accelerates the hydration of both cement and pozzolan. Faster hydration leads to the formation of a denser and more robust gel structure [35].
Additionally, the water vapor present in CC2 facilitates the hydration process and prevents early drying, which can hinder RPC strength development [36]. Notably, CC2 resulted in a more significant increase in compressive strength for mixes with higher pozzolan content. This observation suggests that the beneficial effects of CC2 are amplified in RPCs containing a greater proportion of pozzolan.

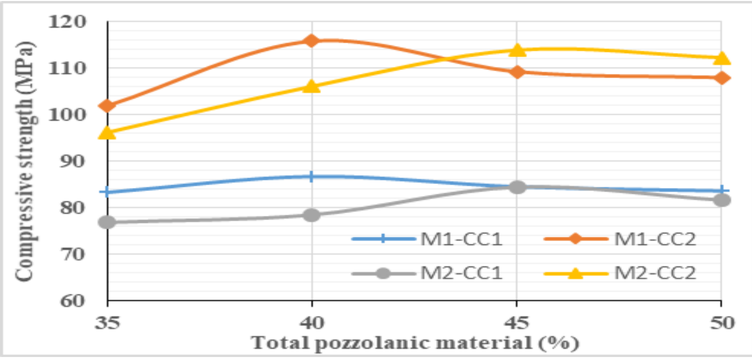

Fig 3. Compressive Strength at 7 Days Age Under Curing Condition 1 and Curing Condition 2

Moreover, Mix M2 exhibited lower compressive strength compared to Mix M1 under CC1. This observation indicates a strong relationship between RHA, SF, and PC within the mix design, which could potentially affect the early-age strength development of RPC. Due to the low curing temperature in CC1, the pozzolanic reaction might have been hindered. This, in turn, could have restricted the formation of C-S-H gel compounds, which are essential for achieving high compressive strength. While CC1 exhibited a substantial increase in compressive strength between 7 and 28 days, the strength gain in CC2 during this period was comparatively modest [30].

4.3. Effects of combined pozzolanic materials on compressive strength

In both curing methods, increasing the pozzolan content generally leads to a rise in the RPC compressive strength. This result can be attributed to two key mechanisms. Firstly, pozzolans react with water and calcium hydroxide (CH) to form essential C-S-H gel compounds, which act as the secondary binding agent in RPC. Secondly, pozzolans fill the pores within the cement paste, thereby increasing its overall density. This densification ultimately results in the production of stronger RPCs.
Interestingly, Mix M1, containing 40% pozzolan (M1-40), and Mix M2, containing 45% pozzolan (M2-40), exhibited comparable compressive strength under both curing methods (CC1 and CC2). In detail, the 7-day compressive strengths achieved by M1-40 and M2-40 in CC1 and CC2 were 86.64 MPa (115.74 MPa) and 84.36 MPa (113.84 MPa), respectively. This trend continued at 28 days, where both mixes achieved similar strengths in both curing treatments: 116.46 MPa (117.74 MPa) and 116.11 MPa (117.25 MPa) for M1-40 (CC1, CC2) and M2-40 (CC1, CC2), respectively. These results suggest that the combinations of 5% SF with 35% RHA offer optimal performance in RPC formulations.
Finally, all mix designs within the M1 and M2 series achieved RPC compressive strengths exceeding 100 MPa under both curing conditions (CC1 and CC2). This finding highlights the effectiveness of the chosen mix design, even with a relatively low cement content of 650 kg/m3 and a combination of low SF and high RHA content.

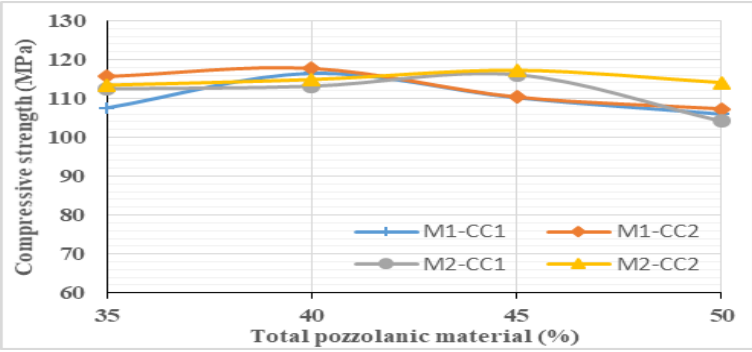

Fig 4. Compressive Strength at 28 Days Under Curing Conditions 1 and 2.

5. Conclusion

This study investigated the combined effects of curing conditions and the use of combined pozzolanic materials (SF and RHA) on the compressive strength of RPC. Specially, it mainly focuses to determine the mixture formulation that produce the highest compressive strength. A novel RPC formulation was developed, incorporating a relatively low cement content (650 kg/m^3) and a combination of low SF and high RHA content. This mix design achieved a compressive strength exceeding 100 MPa at 28 days for normal and steam curing. Based on the analysis, the following conclusions were drawn:

1. Increasing RHA content in the mix stiffens the mixture, due to RHA absorbs more water than SF and increasing SF content from 5% to 10% improves workability and leads to a higher slump flow.
2. Steam curing at 90°C significantly improves compressive strength compared to normal curing due to faster hydration.
3. Increasing the total pozzolan content (SF + RHA) generally leads to higher compressive strength.
4. The combinations of 5% SF with 35% RHA seem to offer optimal performance in terms of compressive strength. This suggests the chosen mix design with a combination of low SF and high RHA content is effective for RPC production.

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