

OPTIMIZING LOCAL RESOURCES IN PAKISTAN TO PRODUCE HIGH-STRENGTH REACTIVE POWDER CONCRETE

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ABSTRACT:

A recently created cementing substance noted for its remarkable qualities is reactive powder concrete (RPC). It incorporates fine quartz sand, crushed quartz, silica fume, a low water-to-cement ratio, and a high percentage of Portland cement. In RPC, fine quartz sand completely takes the role of coarse aggregate. This study examines the effects of high-temperature curing on RPC strength while concentrating on the manufacture of RPC in Pakistan using locally accessible materials. In specifically, a compressive strength of more than 142 MPa is one of the desirable hard qualities that must be attained as the main goal. The study uses a variety of test mixtures and curing methods, including heat curing. The major emphasis is on mechanical properties such as compressive strength, split cylinder strength, and flexural strength. The study also investigates how the mechanical properties of RPC are affected by various steel fiber concentrations and curing conditions. With varying quantities of steel fiber and silica fume, more than 100 experimental mixtures are created. In comparison to silica fume levels, which range between 25% and 35% by weight of cement, steel fiber concentrations range from 0% to 3% by total volume. The results demonstrate the effects of curing at 60°C, 70°C, and 90°C. Notably, after 28 days of curing at 90°C, a compressive strength of 142 MPa is attained, suggesting a general rise in compressive strength across all curing methods with curing age.

1. INTRODUCTION

In the global building business, concrete is a structural material that is often utilized. Exploring cementitious materials that can provide improved mechanical qualities has attracted increasing attention in recent years (Aitcin et al., 1998). Reactive Powder Concrete (RPC) is a relatively new and cutting-edge kind of concrete that has attracted a lot of interest in the building sector. Since its initial introduction in 1994 by French scientists, it has proven to have excellent qualities for a variety of building applications (Richard & Cheyrezy, 1995). RPC is distinctive because of its special formula and production method, which provide a substance with greater consistency, enhanced compacted density, and higher durability. Reactive Powder Concrete (RPC) is one such substance that was initially made available in France in the early 1990s (Dennemann & Reinhardt, 2017). RPC is a cutting-edge cementitious composite that is renowned for its astounding ductility and ultra-high tensile strength. It has a distinct microstructure that makes sure the mixture is

as dense as possible (Li et al., 2021). RPC can reach extraordinary strength thanks to the combination of chemically optimized Portland cement and extensively processed silica fume. RPC was used for the first time during the 1997 building of the Sherbrooke Bridge in Canada (Atcin, 2016). Since then, RPC has been well-known for its exceptional performance in several structural applications, including the successful containment of nuclear waste in Europe (Dennemann & Reinhardt, 2017).

In Pakistan, where space is scarce and the population is expanding quickly, there is an increasing need for high-strength construction materials such as reactive powder concrete. Increased demand for multistory, high-rise reinforced concrete buildings may necessitate greater cross-sections because of the weight of typical concrete (Li et al., 2021). RPC, however, has the benefit of generating cross-sections that are compact while yet having a high compressive strength (Li et al., 2021). Additionally, there is an urgent need for locally available and reasonably priced materials for reinforcing and repairing in a nation like Pakistan that experiences political instability and

continuing wars. The invention of distinctive cementitious materials with enhanced properties is the key contribution of this work (Monshi et al., 2019). According to Cheyrezy and Roussel (1995), as well as Richard and Cheyrezy (1995), Reactive Powder Concrete (RPC) has been recognized as a ground-breaking material that combines great strength with outstanding durability. However, Northern Asia, including Pakistan, has seen little RPC study (Shaheen & Shrive, 2016). In order to comprehend RPC's potential uses in the construction industry, it would be helpful to investigate how it is made utilising readily available materials and straightforward manufacturing processes (Dennemann & Reinhardt, 2017). Following are the study's primary goals: (1) To examine the RPC manufacturing process in Pakistan using locally accessible ingredients and appropriate mixing techniques, (2) To conduct a parametric analysis to assess the effects of admixture dosage, steel fibers, filler materials, silica fume concentration, and mixing procedures on RPC's properties, (3) To evaluate the mechanical properties of RPC, including compressive strength, splitting tensile strength, hardened density, and flexural strength, (4) To investigate the RPC manufacturing process in Pakistan using locally available ingredients and suitable mixing.

This study included a thorough review of the literature on RPC, the selection of locally accessible resources for RPC production (such as cement, silica fume, steel fibers, and plasticizers), the determination of mix proportions, and physical and mechanical testing of RPC samples. The RPC specimens' compressive strength, splitting tensile strength, and flexural strength were all be evaluated throughout the testing. By focusing on these goals, the study hopes to further knowledge of reactive powder concrete and its possible applications in Pakistan's construction sector.

2. MATERIALS AND METHODS

The physical characteristics of hardened concrete were tested as part of this study's laboratory investigation. The Reactive Powder Concrete (RPC) for the study's experiments and raw ingredients are presented in this chapter. The mechanical properties, compressive strength, workability, and density of RPC were examined in various tests on hardened concrete, including compression strength tests and indirect tensile testing (split cylinder and flexural strength tests). These tests included silica fume doses, steel fiber amounts, and curing regimes. Examples of the test procedures, tools, and information used to assess the properties of concrete are given in this section.

2.1 Constituent Ingredients of RPC

Cement, which serves as a binder, is a substantial component of RPC materials. To improve the mechanical properties, more fibers are employed as well as filler materials like quartz powder and silica fume.

2.2 Ordinary Portland cement

The performance of RPC is greatly influenced by the cement choice. The use of cement with a high concentration of di- and tricalcium silicate (C3S and C2S) and little to no tricalcium aluminate (C3A) is advised. C3A is primarily present in cement because it serves as a flux during the calcination process, and its intrinsic usefulness as a binding agent is quite low. Raising concrete strength without significantly increasing cement content is crucial to achieving high-strength concrete. Mineral admixtures have been suggested as viable RPC cement substitutes. (Muhammad Adil Sultan et al., 2023) (fig.1).



Figure 1. Ordinary Portland cement

2.3 Silica Fume

To increase concrete's compressive strength and prevent damaging alkali-silica interaction, silica fume is frequently employed. It enhances the permeability for plastic shrinkage cracking while decreasing the likelihood for segregation. Silica fume is routinely added to cement or concrete because of its potent pozzolanic properties (Houssam & Ziad, n.d.) It alters the microstructure of concrete and makes a physical and chemical contribution to the changes (fig.2).



Figure 1. Silica Fume

2.4 Quartz Sand

Due of its great rigidity, quartz—the most common kind of pure silica in nature - is utilised in RPC. It provides good paste/aggregate interfaces and is inexpensive and easily available (Khayat & Manai, 2017). For quartz sand, a suggested range of particle sizes is 150 to 600 μ m to prevent interaction with the biggest cement particles (fig.3 and table 1).



Figure 2. Quartz Sand

Sieve size(mm)	0.600	0.300	0.150	0.075
% Passing	100	37.60	1.00	0.20

Table 1. Grading of Quartz Sand

2.5 Water

All concrete mixtures and specimen curing procedures utilised potable water. The amount of water used in a concrete mix, which defines the water-cement ratio, has an impact on the concrete's strength and longevity. Lower water-to-cement ratios boost strength and durability at the expense of potential mixing and shaping difficulties. To address workability difficulties, plasticizers and super-plasticizers can be utilised.

2.6 Superplasticizer

Chemical admixtures called superplasticizers, commonly referred to as high-range water reducers, are used in concrete mixes to disperse cement and silica fume (Monshi et al., 2019). They make the combination more durable, easier to deal with, and need less water overall. Superplasticizers make it possible to employ lower water-cement ratios without compromising workability, resulting in concrete that is stronger and has superior placement workability.

2.7 Steel Fibers

The brittleness of high-strength concrete is addressed by adding steel fibers to the RPC matrix to enhance its flexibility. To boost toughness without considerably reducing the material's strength, modest quantities of fibers—typically between 1% and 6% by volume—are included into the concrete mixture (Ahsan et al., 2023). The parameters of steel fibers used in RPC are generally length, diameter, length-to-diameter ratio, tensile strength, and density (fig.4).



Figure 4. Steel Fibers

2.8 Experimental Development

The goal of the experimental programme was to determine how different factors affected the density, workability, compressive strength, and mechanical characteristics of reactive powder concrete (RPC). On hardened concrete, the following experiments were carried out:

2.9 Sample size parameters

The batch plant in the lab had a capacity of three samples per batch. Below is a list of a single cylinder's measurements. The beam has dimensions of 100 x 100 x 500 mm. The cylinder is 150 x 300 mm in size (fig.5).

The total number of samples is 102, and they were all cast in 90 days. Material Weighing Weigh the materials to determine their weights using a battery-powered balance. Each ingredient is weighed out separately and put in its own pot. Put every container holding weighted material close to the batching facility. Then mixing and filling to mouldes with ASTM standards utilized.



Figure 5. The casted cylinder and beams

2.10 Testing Parameters

This project complied to the following two rules:

(a) To explore the behavior of RPC, variations in steel fiber ratios were seen between normal temperature ranges of 25°C and 90°C.

(b) RPC was tested at three distinct high temperatures (60, 75, and 90 degrees Celsius) while preserving a constant steel fiber ratio.

(c) Different temperatures' effects on RPC density behavior were also noticed.

The experimental program changed the following parameters:

- Different amounts of silica fume were added to the RPC combinations to examine how they affected the mechanical characteristics.
- Steel fiber quantity: To learn more about how steel fibers affect the ductility and hardness of the concrete, different quantities of steel fibers were added to RPC combinations.
- Quartz sand, used as a fine aggregate in RPC mixtures, plays a crucial role in enhancing the overall workability, density, and compressive strength of the concrete.

Curing regime: Various curing regimes, including normal curing and accelerated curing procedures were used to assess their impact on the development of RPC's strength and durability.

2.11 Data Collection and Analysis

Data on the compressive strength, split tensile strength, and flexural strength of RPC specimens were gathered throughout the testing programme. To ascertain the influence of the various factors on the mechanical characteristics of RPC, the acquired data were statistically analyzed. Regression analysis and analysis of variance (ANOVA) were used to identify correlations between the parameters and the concrete qualities and to determine the significance of the experimental variables. To make comprehension and comparison easier, the results were provided in graphical and tabular formats.

2.12 Methods of Curing

In order to properly cure concrete, the water evaporation rate must be controlled, and the cement must have enough time to hydrate. The difficulties of curing are exacerbated in hot weather because of increased temperatures and quicker evaporation. Particularly in warmer conditions, the early curing period is crucial in establishing the concrete's qualities, such as compressive strength, flexural strength, and elastic modulus (Houssam & Ziad, n.d.). The intended usage of the concrete and external factors like humidity and temperature affect the cure period. Inadequate curing can result in imperfections, permeability, decreased strength, and limited durability (Khan & Ayers, 1998). In order to improve mechanical qualities such compressive strength, splitting tensile strength, and flexural strength, this study analyses various curing techniques and delays.

NC stands for "Normal Water Curing" (submerge in water at 25°C till testing day).

HC60-1 stands for Hot Water Curing at 60°C for 1 day after setup and then immersion in water at 25°C till testing day.

HC60-2 at 60°C for two days after setting of immersion in 25°C water until the day of testing, followed by a hot water cure.

HC60-3 "Hot Water Curing at 60°C for 3 days after setting" and "25°C until day of testing."

HC75-1=Hot Water Curing for 1 day at 51 °C after setting, then immersion in 25 °C water till the day of testing.

HC75-2 is heated to 51°C for two days after setting, then submerged in 25°C water until the day of testing.

HC75-3 = Hot Water Curing for 3 days at 51 °C after setting, followed by immersion in 25 °C water till the day of testing.

HC90-1 stands for Immersion in Water at 25 °C Up to Testing Day and Hot Water Curing at 90 °C for One Day After Setting.

HC90-2 Hot Water Cured for 2 days at 90 °C after setting, then submerged in 25 °C water until the day of testing.

HC90-3 Hot water Cured for three days at 90 °C after setting, then submerged in 25 °C water until the day of testing.

2.13 Curing Tank

The curing tank is specifically for the hot water curing of concrete with increased strength. Stainless steel is used to make the inside. For a completely automated curing cycle, the control system may give the curing container with various temperature gradients at any time at a predefined temperature. The curing tank is shown in the figure 6. It had the following specifications: a thermostat, heaters, and a 6x4x3 foot size.



Figure 6. Curing Tank

3. RESULTS AND DISCUSSIONS

The experiments on hardened reactive powder concrete (RPC) were performed in order to assess its mechanical characteristics. This chapter examines the effects of steel fiber ratios and curing temperatures on RPC as well as the findings of numerous tests conducted as part of the testing program. Unit weight, compressive strength, splitting tensile strength, and flexural strength tests were performed. The ideal compressive strength was measured using about 100 different cube specimens (4" x 4" x 4"). After 14 days of casting, the sample had 151 MPa of strength. The toughened properties of RPC were examined through laboratory testing with various mix designs and different steel fiber ratios. The results cover compressive strength, secondary tensile strength, and flexural strength. The resulting conclusions are as follows:

Findings of Normal Water Curing in Hardened Characteristics and Hot Water Curing under Various Steel Ratios

Laboratory testing was used to study and assess the RPC's toughened properties. Results are produced by various blend designs. In addition to their flexural strength, secondary tensile strength, and compressive strength, they also have 0% steel fiber. Below is a brief description of the findings.

- A. 1% steel fibers
- B. 2% steel fibers
- C. 3% steel fibers

Hardened characteristics are formed throughout a range of temperatures

The laboratory testing conducted for this study shows that Mix M3-2 contains both the ideal silica fume value of 30% and the ideal steel fiber level of 3%. With the aid of this mixture, it was possible to assess how the curing procedure changed RPC's mechanical and physical properties.

How curing techniques affect RPC Density

Figure 7 summarizes the effects of several curing methods on the RPC unit weight. The results show that concrete density decreases as heat-treating temperature is increased.

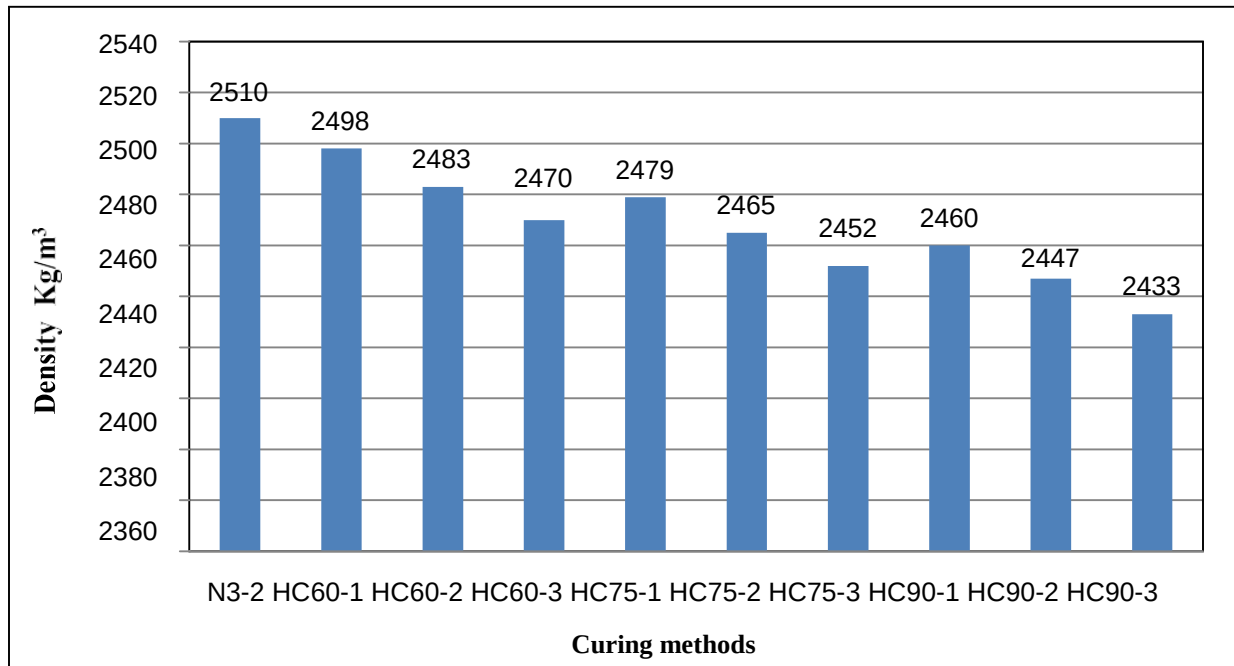


Figure 7. Density of All Curing Methods

Effects of curing techniques on RPC's compressive strength

Compressive strength:

The compressive strength was determined by breaking the 150 mm concrete cubes in a MATEST compression-testing device in accordance with BS 1881 part 116:1983 requirements and averaging the outcomes of three samples for each mix. The bulk of the Mixes were tested 7, 14, and 28 days after casting. The results of compressive strength testing for all specimens and in all conditions are displayed in Tables 2, and Figures 7. The average of three samples makes up each number.

Curing methods	Compressive strength MPa			Increasing of compression strength at 28 day (%)
	7 days	14 days	28days	
NC3-2	76	100	123	0
HC60-1	77	104	128	4
HC60-2	87	107	135	12
HC60-3	86	109	137	10

HC75-1	84	106	131	7
HC75-2	88	116	145	19
HC75-3	89	113	140	14
HC90-1	86	105	133	8
HC90-2	100	132	146	19
HC90-3	92	114	142	16

Table 2. Compressive strength of RPC due to the curing method

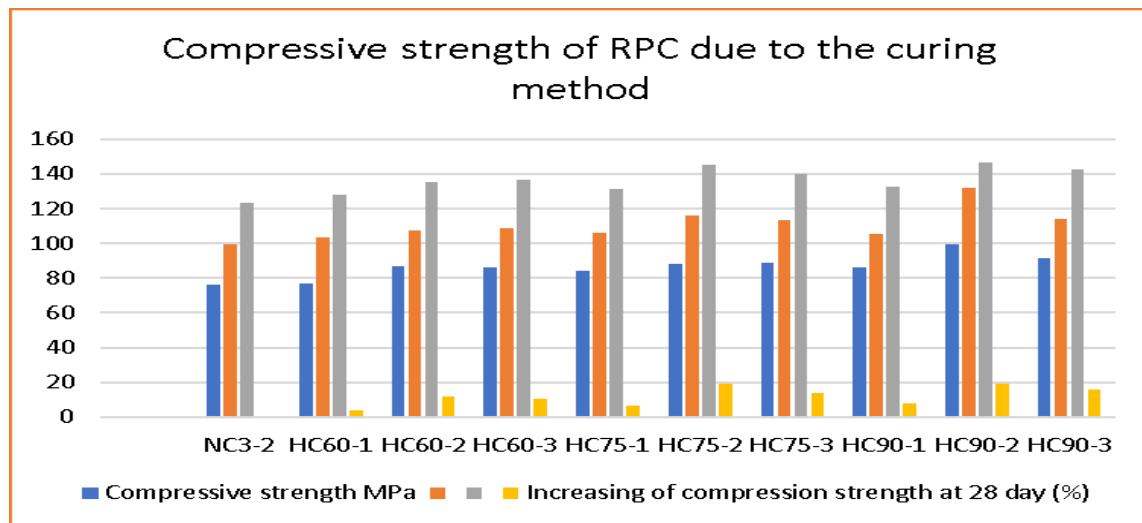


Figure 7. Compressive strength of RPC due to the curing method

After 28 days of HC90-2 curing, Reactive Powder Concrete (RPC) exhibits a considerable increase in compressive strength, reaching 145.46 MPa. These findings are consistent with earlier research by (Journal of Engineering and Development, 2013). Up until the 28th day, a consistent increase in RPC strength was seen every day. Higher temperatures hasten hydration, which hastens the development of strong compressive strength. After 28 days, HC60-1 has the lowest compressive strength of all the curing methods, at 125.90 MPa. Comparatively, after 28 days of curing using various procedures, the compressive strength of RPC grows by 4.00% to 19.19%, with a 5.7% increase when the temperature climbs from 60°C to 90°C in three days.

Tensile strength of RPC breaking and curing method effects

Tensile Strength for Splitting

Reactive Powder Concrete (RPC) steadily gains tensile strength, with the HC90-2 curing method providing the highest strength after 28 days. Up to day 28, RPC's tensile strength grows steadily every day, with higher temperatures speeding hydration and hastening the development of strength. The increase in tensile strength caused by various curing methods ranges from 5 % to 20 %. An experiment

with a 28-day split tensile test was conducted using nine different curing methods. The strength of the cylinders gradually increases as the temperature increases from 60°C to 90°C.

Curing methods	Splitting tensile strength MPa	Increasing of Splitting tensile strength At 28 day (%)
M3-2	12	0
HC60-1	13	10
HC60-2	15	28
HC60-3	18	57
HC75-1	17	45
HC75-2	17	51
HC75-3	19	74
HC90-1	16	38
HC90-2	17	49
HC90-3	20	82

Table 3. Effect of various days curing after 28 days on splitting tensile strength

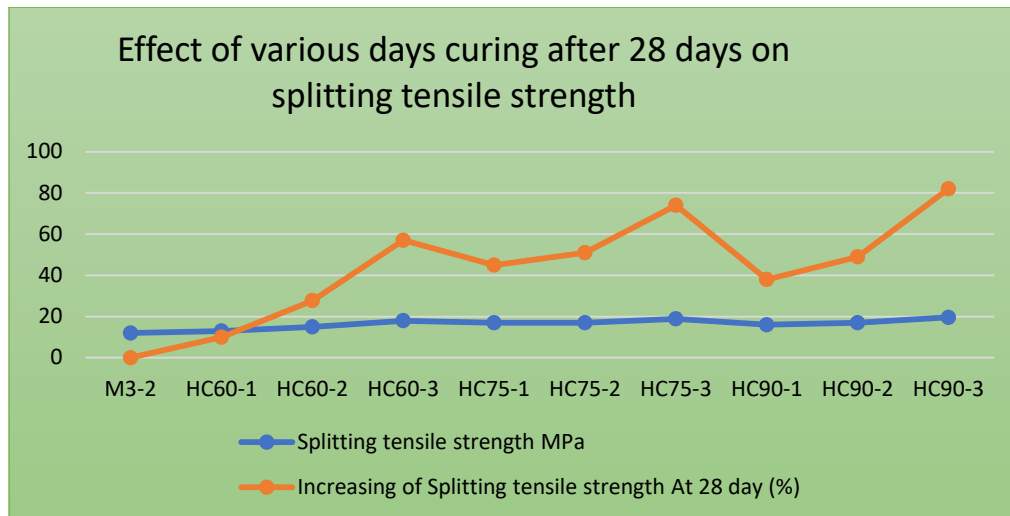


Figure 8. Effect of various days curing after 28 days on splitting tensile strength

Curing techniques' effects on RPC flexure strength Flexural Strength

The three-point bending test is regarded as being the most important for analysing the behaviour of composites made of fiber-reinforced concrete. The flexural strength of a sample of RP concrete was evaluated using ASTM C78-02. The flexural strength of reactive powder concrete (RPC) gradually increases, with the maximum strength being

shown at the 28-day mark of the HC90-2 curing process. By taking advantage of faster hydration at higher temperatures, which accelerates the rate of strength development, RPC's flexural strength continuously grows every day until day 28. The increase in flexural strength produced by various curing methods ranges from 4 % to 19%.

Curing methods	Flexural tensile strength MPa	Increasing of flexural tensile strength at 28 day (%)
M3-2	21	0
HC60-1	22	4
HC60-2	25	19
HC60-3	27	29
HC75-1	23	8
HC75-2	26	26
HC75-3	22	4
HC90-1	23	9
HC90-2	25	22
HC90-3	23	11

Table 4. Effect of various days curing after 28 days on splitting tensile strength

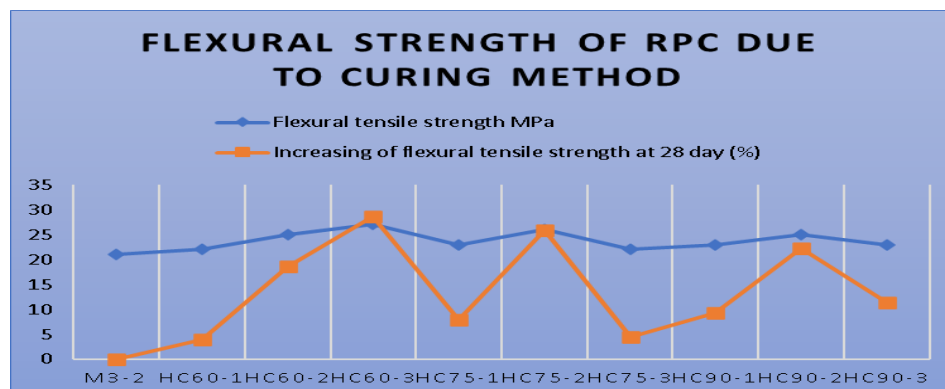


Figure 9. Comparison of Splitting flexural after 28 Days at Different Curing Temperature

High compressive, tensile, and flexural strength, little porosity, longevity, and self-compacting characteristics are all characteristics of RPC, a popular form of concrete. This study aims to construct RPC using locally accessible materials in Pakistan and assess its mechanical behavior through laboratory testing. Heat curing at various temperatures and lengths showed a noticeable increase in strength, which facilitated the quick production of high-strength cement-based products. Compared to ambient curing, higher temperatures accelerated the growth in strength. It is noteworthy that specimens that were cured at 25°C for 56 days exhibited strength comparable to those that were cured at 90°C for 2 days. This result has positive ramifications for speeding up construction when RPC technology is properly applied.

4. CONCLUSIONS

RPC made in Pakistan using materials found on the local market has a compressive strength after 28 days at 25°C of 125 MPa and after 28 days with a two-day cure at 90°C of 142 MPa. RPC in precast concrete allows for heat-curing compressive strengths more than 142 MPa. Such concretes can be made using steel fibers at 3% volume, quartz sand at 100%, and silica fume at 25% of cement weight. Under the same water-to-cement ratio, hot-cured RPC displays greater compressive, splitting tensile, and flexural strength than regular-cured RPC. Lower w/c ratios prevent full compaction while higher ratios cause air bubble entrapment and decreased strength. Compressive strength is positively impacted by steel fiber dose. Strength for compressive, splitting tensile, and flexural tests is increased by higher temperatures and longer curing durations. At 25 °C, strength increases by 49.68%, 11.47%, and 13.52% when steel fiber content is increased from 0% to 3%; at 90 °C, the strength increases by 43.30%, 3.88%, and 35.42%. With higher curing temperatures and longer curing times, density drops. With higher curing temperatures and longer curing times, RPC's splitting tensile and flexural strengths increase.

5. RECOMMENDATIONS

Key suggestions for additional study based on this investigation include:

- Investigating how the mechanical properties of RPC are affected by the type of cement and steel fiber aspect ratio.
- Evaluating the RPC's resistance to wear and tear, including its performance at high temperatures, permeability, procedure for developing strength, and fire and chemical resistance.
- Examining the creep, drying shrinkage, stress-strain behaviour in compression and tension, static and dynamic modulus, and other short-term mechanical properties of RPC evaluating the efficacy of various curative methods in numerous research facilities.
- Investigating the effects of curing on the

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