

EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF METAKAOLIN AND QUARRY DUST IN CONCRETE

Nilesh Parmar^{1,2,*}, Kondraivendhan B.¹, and Hariom Khungar^{1,3}

Received: November 06, 2024; Revised: February 14, 2025; Accepted: February 27, 2025

Abstract

The increasing demand for sustainable and high-performance concrete has driven the exploration of alternative materials to enhance its properties. Ordinary Portland Cement (OPC) production significantly contributes to carbon emissions, necessitating the incorporation of supplementary cementitious materials like metakaolin and quarry dust. This study investigates the combined effect of these materials on the mechanical properties of concrete, aiming to optimize its strength and sustainability. A mix design with a 1:1.62:2.89 ratio of cement, coarse aggregate, and fine aggregate was prepared with varying percentages of metakaolin (10% and 12%) and quarry dust (14%, 16%, and 18%). Experimental tests, including compressive, tensile, and flexural strength evaluations, were conducted at curing intervals of 3, 7, and 28 days. The data were analyzed using statistical techniques such as Analysis of Variance (ANOVA) and Multi-Criteria Decision Making (MCDM) with Taguchi optimization to determine the significance of different parameters and optimize the mix design. Results revealed that the incorporation of metakaolin and quarry dust significantly enhanced the mechanical properties of concrete. The highest compressive strength of 40.6 MPa was achieved with 12% metakaolin and 18% quarry dust after 28 days of curing, showing a remarkable improvement over conventional concrete. Similarly, split tensile and flexural strength also exhibited notable increases, with optimal strength achieved at 12% metakaolin and 16% quarry dust. Statistical analysis confirmed the significant impact of these additives, with quarry dust emerging as the most influential factor in compressive strength improvement. This study underscores the potential of metakaolin and quarry dust as effective supplementary materials, promoting both strength enhancement and sustainability in concrete production. The findings contribute to advancing concrete technology and offer a viable approach for eco-friendly construction practices.

Keywords: Concrete optimization; Mechanical properties; Metakaolin; Quarry dust; Self-healing concrete; Statistical analysis; Sustainable construction

¹ Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology, Surat, India. E-mail: nilesh.dip83@gmail.com*; bkvv@amd.svnit.ac.in; khungarhp@rknc.edu

² Civil Engineering Department, GIDC Degree Engineering College, Navsari, India.

³ Civil Engineering Department, Ramdeobaba University, Nagpur, India.

* Corresponding author

DOI: <https://doi.org/10.55766/sujst7333>

Suranaree J. Sci. Technol. 32(2):010357(1-19)

Introduction

Concrete construction has evolved significantly over the years, marked by advances aimed at enhancing strength, durability and environmental sustainability. Historically, concrete compositions evolved from primitive mixtures of stones and binders to the improved use of Portland cement in the 19th century, which laid the foundation for modern concrete applications. However, the environmental impact of large-scale cement production has prompted the search for alternative materials and additives to mitigate this impact. In 2023 alone, global cement production increased to approximately 4.1 billion tons to meet the demands of infrastructure development and 3.5 billion tons of carbon dioxide emission (Sverdrup and Olafsdottir, 2023). This huge carbon footprint highlights the urgent need for sustainable practices in the construction industry. Efforts are being made to integrate alternative cement-based materials from agriculture, industry or the sea to improve the sustainability of construction practices. Recycling waste materials to replace cement not only benefits the environment, but also promotes sustainable construction practices. Materials containing silicon (Si) and aluminium (Al) are in particular demand for their pozzolanic properties, which improve concrete performance and reduce environmental impact. Mineral admixtures such as fly ash, ground blast furnace slag (GGBS), metakaolin, quarry dust and silica fume play a vital role in both improving the performance of concrete and reducing its environmental impact. Fly ash, a byproduct of coal combustion, has been crucial to concrete production (Thomas *et al.*, 2012) since the 1950s, and early research by McMillan and Powers in 1934 pioneered the use of coal as a fuel source in the manufacture of concrete, paving the way for the widespread use of fly ash as a supplementary cementitious material (Fulton and Marshall, 1956) in the 1950s increased understanding, leading to widespread use. The addition of fly ash to concrete significantly improves the performance of the concrete. The optimum replacement level of fly ash was approximately 20% at a plasticizer dose of 2.4% binder (Wild *et al.*, 1996). This replacement level improves the compressive strength, flexural strength and durability of concrete while reducing its environmental footprint. Despite the many advantages, the use of fly ash is associated with challenges. Fluctuations in fly ash quality and processing difficulties lead to important considerations in concrete mix design and construction. Careful attention to acquisition and quality control is important to ensure consistent

performance and reduce potential problems in real-world applications. Ground Granulated Blast Furnace Slag (GGBS) from steelmaking processes offers a sustainable alternative to traditional cementitious materials. Adding it to concrete not only improves its performance, but also reduces the environmental impact of concrete production. The role of GGBS in controlling adverse alkali-silica reactions in concrete, contributing to its long-term durability (Blanks, 1949). The silica fume obtained during the cleaning of silica admixtures plays a crucial role in improving the strength and durability of concrete. Research by (Nafees *et al.*, 2021) highlighted significant improvements in sustainability of concrete with the addition of silica fumes. In addition, (Kim *et al.*, 2019) showed that the addition of silica fume to concrete mixes significantly improves overall mechanical properties. Metakaolin obtained by controlled calcination of kaolin clay has received considerable attention in concrete research due to its remarkable pozzolanic reactivity and performance-enhancing properties. Further studies by (Duan *et al.*, 2013) confirmed these results, emphasizing the role of metakaolin in improving the dimensional stability of concrete over time. Hassan *et al.* (2010) investigated the ability of metakaolin to improve and presents its potential to extend the service life of concrete structures. Yuan *et al.* (2023) explored the microstructural changes induced by metakaolin and investigated its role in densifying the concrete matrix and refining the pore structure, which improves mechanical properties. In addition, Park *et al.* (2021) investigated the effect of metakaolin on the sustainability aspect of concrete production, focusing on its environmental benefits, such as reducing carbon dioxide emissions and energy consumption during curing processes. Zhang *et al.* (2021) investigated the effect of metakaolin on the rheological properties of concrete, revealing its potential to improve workability and reduce segregation, thus improving construction efficiency and quality control. A recent study by Dou and Xu (2023) investigated the long-term performance of concrete containing metakaolin, highlighting its ability to reduce the porosity and defects and strengthen the bonding in interfacial transition zone. Zhang *et al.* (2021) reviewed the economic viability of using metakaolin in concrete production and highlighted its potential cost savings and economic benefits to the construction industry. According to several researchers, the increased pozzolanic activity of metakaolin also contributes to a refined pore structure and improved interfacial transition

zone, which is critical for high-performance concrete applications. Sabir *et al.* (2001), the addition of metakaolin significantly increases the early strength of concrete, which provides an advantage in accelerated construction projects. In addition, Li *et al.* (2015) noted that metakaolin can reduce permeability, which improves the resistance of concrete to sulphate attack and chloride intrusion, which is critical for marine environments or infrastructure exposed to deglaciation salts. The sustainability aspect is further supported by Kurtis (2015), who found that metakaolin-modified concrete has a lower carbon footprint compared to traditional Portland cement mixes, mainly due to reduced clinker content and better durability. In addition, Figueira *et al.* (2015) showed that metakaolin can effectively reduce the alkali-silica reaction, a common cause of concrete damage, thus extending the service life of concrete structures and reducing maintenance costs. Quarry dust, a by-product of aggregate production, is also a sustainable alternative to river sand in concrete production. Its use in concrete not only reduces the environmental impact associated with sand mining, but also improves the structural properties of the concrete. Studies by Jagadeesh *et al.* (2016) investigated the mechanical properties of concrete containing quarry dust and demonstrated its ability to significantly improve compressive strength. This study revealed that the compressive strength of concrete mixes containing quarry dust increased by 10-15% compared to traditional mixes. The study by Silva *et al.* (2023) focused on durability and emphasized the role of quarry dust in improving chloride penetration and sulphate resistance, which extends the service life of concrete structures in aggressive environments. Their results showed that concrete containing quarry dust improved its resistance to chloride penetration and sulphate attack was reduced, making it suitable for use in coastal and industrial areas. Ibraheem *et al.* (2021) delved into the microstructural changes caused by quarry dust and explained its role in improving the pore structure and interfacial transition zone, which improves the mechanical and durability properties of concrete. Their research showed that quarry dust reduces the porosity of concrete, resulting in a denser matrix and better bonding at the aggregate-cement interface. This improvement improves durability and mechanical properties such as increased compressive and flexural strength. In addition, (Singh *et al.*, 2016) investigated the environmental impacts of using quarry dust, highlighting its potential to reduce environmental impacts associated with sand mining and promote sustainable construction practices. In addition, the feasibility of usage of quarry dust in concrete was

reviewed and found it to be more cost efficient than conventional mixes (AL-Kharabsheh *et al.*, 2022). The decision to use metakaolin and quarry dust over other supplementary cementitious materials (SCM) is due to their superior performance and clear advantages proven by extensive research. A study by Anupama *et al.* (2011) is particularly illuminating, showing that a combination of metakaolin and quarry dust not only improves rheological properties but, also significantly reduces chloride permeability compared to other SCM mixes. This unique synergistic effect highlights the effectiveness of these materials in creating stronger and more durable concrete. In addition, metakaolin has been highlighted in research for its excellent ability to improve the microstructure of concrete. According to (Thankam and Thurvas, 2020), metakaolin refines the pore structure, which significantly improves the mechanical properties and durability of concrete. In addition, the environmental and economic benefits of quarry dust further justify its use in concrete applications. The use of pit dust helps mitigate the environmental impacts of excessive sand mining. Economically, the addition of quarry dust reduces the cost of concrete because it is available as a by-product of rock crushing processes. These cost efficiencies combined with environmental benefits fit well with the global sustainable development of the construction industry. This versatile utility makes metakaolin and quarry dust not only a technical choice to improve the properties of concrete, but also a strategic choice to achieve economic and environmental sustainability in construction activities.

Statistical analysis of variance (ANOVA) using MINITAB software is used in this study to ensure accurate evaluation of mechanical properties of concrete containing metakaolin and quarry dust. ANOVA is crucial for determining the significance of different parameters in specific responses at a 95% confidence level and effectively handles complex relationships between multiple responses. This method has played a key role in concrete research in evaluating the effects of different additives and mixing forms. In addition to ANOVA, MCDM (Multi-Criteria Decision Making) is used to solve the evolving complex problems of concrete mix design, moving from a single-criteria decision environment to a multi-criteria decision environment. Experimental design methods are essential in this study to achieve reliable results by carefully selecting variables and levels that minimize variation and error. By integrating advanced statistical methods such as ANOVA and MCDM with experimental design methods, this study aims to significantly improve the understanding and optimization of concrete

properties by ensuring the effective use of alternative materials such as metakaolin and quarry dust to improve mechanical properties, durability and environmental protection sustainable development. By choosing metakaolin and quarry dust, this study uses their superior pozzolanic activities, strength and synergistic advantages to optimize concrete properties, providing both environmental and structural benefits. The integration of these materials, supported by advanced statistical methods and experimental designs, aims to create new metrics for concrete performance and durability.

Despite the known benefits of metakaolin and quarry dust, several key research gaps are studied, the most studies have individually assessed the effects of metakaolin or quarry dust in concrete, with limited research exploring their combined influence on compressive, tensile, and flexural strength. The optimization of mix proportions using advanced statistical models such as Analysis of Variance (ANOVA) and Multi - Criteria Decision Making (MCDM) with Taguchi optimization has not been adequately explored. Existing studies lack a systematic methodology integrating experimental validation, statistical modeling, and numerical simulations to optimize mix design effectively.

To address these research gaps, the present study aims to:

1. Investigate the combined effect of metakaolin and quarry dust on the mechanical properties of concrete, specifically compressive strength, split tensile strength, and flexural strength.
2. Optimize mix proportions using ANOVA and MCDM with Taguchi optimization, ensuring a systematic approach to maximize concrete performance.
3. Develop and validate a numerical model using Finite Element Method (FEM) simulations in ABAQUS/ANSYS, providing predictive insights into stress-strain behavior.
4. Establish a scientifically validated framework for integrating metakaolin and quarry dust in concrete production, promoting sustainability and durability in construction.

From the above literature review has been observed that metakaolin and quarry dust in concrete have been used to study experimental and analytical approach. Based on the above study following novelties are proposed in the present study.

1. Optimized Mix Design: The study identifies an optimal mix of 12% metakaolin and 18%

quarry dust, achieving a maximum compressive strength of 40.6 MPa at 28 days, significantly improving conventional concrete strength.

2. Enhanced Mechanical Performance: The addition of these materials resulted in higher split tensile and flexural strengths, with optimal tensile strength achieved at 12% metakaolin and 16% quarry dust.
3. Statistical Validation: ANOVA confirmed that quarry dust was the most influential factor in enhancing compressive strength, followed by metakaolin. The MCDM approach demonstrated the effectiveness of multi-parameter optimization in concrete mix design.
4. Sustainability and Waste Utilization: This study demonstrates the potential of replacing a portion of cement and fine aggregates with metakaolin and quarry dust, contributing to eco-friendly construction practices by reducing cement consumption and utilizing industrial waste.
5. Unlike previous studies that examined these materials in isolation, this research explores their combined effect and employs advanced statistical techniques to achieve an optimized and scientifically validated mix design. The findings provide a framework for sustainable concrete production, paving the way for improved material efficiency and long-term durability in modern construction.

Materials and Methodology

The raw materials chosen as binders include OPC of grade 53, Metakaolin, and Quarry dust. The detailed physical properties which subsidize the objective of the study are explained below.

Cement

The cement had a specific gravity of 3.15, indicating its density compared to water. Its physical form was a fine powder, facilitating easy mixing and application. The color of the cement was grey, providing a standard visual indicator commonly associated with the material.

Metakaolin

Metakaolin appeared as an off-white powder with a specific gravity ranging from 2.4 to 2.6, indicating its density relative to water. Its density was measured at 2640 kg/m³, and it exhibited a brightness of 76%, with particle sizes averaging at 12µm. The residue on 375 mesh screens was kept to a maximum of 0.5%, ensuring a high level of purity and uniformity in particle size distribution.

Quarry Dust

Quarry rock dust is a business. it's miles fashioned by way of screening merchandise of secondary and next levels of crushing igneous rocks, sedimentary rocks, or gravel. it could be classified through the size of the debris as 0 to 4.75 mm. Presently a large amount of quarry rock dirt is generated in herbal stone processing plant life. Quarry rock dust is cheap and extensively to be had in the course of the world. it's miles fashioned from waste fines of crushed products of stone (gravel) in crushing plants. The quantity of waste at every quarry reached 13-15% of crushed stone with the aid of a mass-based survey taken from 13 places in Dindigul District, Tamil Nadu, India. Figure 1 shows the area of quarries at numerous locations in Dindigul District. Total 13 samples have been accumulated from special quarries located throughout the district. All samples had been accumulated within 7 days from the crushing date. The physical and chemical homes of the accrued samples have been tested. Out of 13 samples, the sample accumulated from Q1 became used for the complete experimental work, because sieve evaluation consequences and different residences were very close to zone II of IS 383.

Characterization of the quarry rock dust varied from place to place based on crushing methods and machinery. So, a detailed study was carried out to ascertain the extent of variability of the physical and chemical properties of the quarry rock dust from thirteen crushing plants in Dindigul district, Tamil Nadu state, India.

The decision to use metakaolin and quarry dust was driven by their superior performance and clear advantages demonstrated through literature review carried out. Metakaolin exhibits excellent

pozzolanic reactivity, which refines the pore structure and improves the mechanical properties and durability of concrete. Quarry dust, on the other hand, is a sustainable alternative to river sand that not only reduces environmental impacts associated with sand mining but also enhances the structural properties of concrete. Additionally, quarry dust is cost-effective and widely available, making it an economically viable choice.

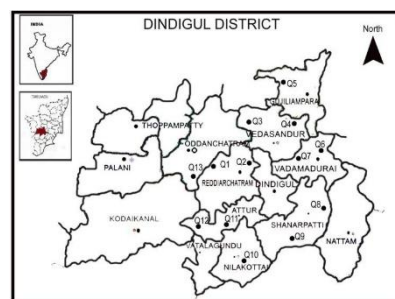


Figure 1. Location of Sample Collected Quarries at Dindigul District (Q1 to Q13)

Coarse Aggregates

Table 1 presents the physical and mechanical properties of coarse aggregates, detailing sieve size requirements, specific gravity, water absorption, aggregate impact value, bulk density, flakiness, and elongation as per IS: 383-1970 standards.

Fine Aggregates

Table 2 outlines the percentage passing of fine aggregates through various I.S. sieves as per IS 383 standards, along with additional properties such as fineness modulus, specific gravity, bulk density, bulking of sand, and silt content, providing insights into the characteristics of the material.

Table 1. Physical and mechanical properties of coarse aggregates

Sieve Size (mm)	20 mm		10 mm	
	Requirement as per IS: 383-1970	Percentage passing	Requirement as per IS:383-1970	Percentage passing
80	--	--	--	--
63	--	--	--	--
40	100 %	100 %	--	--
20	85 – 100 %	94.60 %	--	--
16	--	--	100 %	100 %
12.50	--	--	85 -100 %	93.4 %
10	0 – 20 %	14.30 %	0 – 45 %	39.23 %
4.75	0 – 05 %	2.85 %	0 – 10 %	6 %
2.36	--	--	--	--
Specific gravity		2.80	--	2.70
Water Absorption %		0.40	--	0.49
Aggregate Impact Value		12.5 %	--	13 %
Bulk Density (kg/m ³)		1670	--	1665
Flakiness		13.5 %	--	14 %
Elongation		14 %	--	--

Chemical properties

The chemical composition of cement, metakaolin, and quarry dust is presented in Table 3, where the percentage composition of key elements including silica, alumina, calcium oxide, ferric oxide, magnesium oxide, potassium oxide, and sulphuric anhydride is highlighted, offering insights into their respective proportions within the materials.

Experimental Study

In this study, self-healing concrete is made using cement, metakaolin, quarry dust, coarse aggregate, fine aggregate, and water. A mix proportion of 1: 1.62:2.89 ratio of cement, coarse aggregate (C.A), fine aggregate (F.A), and 0.5 w/c ratio was used along with varying percentages of metakaolin, and quarry dust as shown in Table 4. In the initial stage mixes of conventional concrete were tested. Later in the second stage mixes of concrete with the addition

of 10% and 12% metakaolin and 14%,16%, and 18% quarry dust were prepared for testing. The details of mixed proportions and their designations are as tabulated in Table 5.

In the lab, three types of tests were performed: compressive strength, split tensile strength, and flexural strength. Each test was assigned specific dimensions for the specimens: cubes of $150 \times 150 \times 150$ millimeters for compressive strength, cylinders of 150×300 millimeters for split tensile strength, and prisms of $500 \times 100 \times 100$ millimeters for flexural strength. A total of 54 specimens were allocated for each test, resulting in a cumulative total of 162 specimens. This structured approach ensured a thorough assessment of the material's strength characteristics under diverse loading conditions, contributing to a comprehensive understanding of its performance in practical applications.

After casting the specimens are molded after 24 h and left for water curing for a period of 3,7,28 days. Upon curing, the specimens are allowed to air

Table 2. Physical and mechanical properties of fine aggregates

I.S. Sieve (mm)	Percentage Passing through I.S. Sieve	Percentage Passing I.S. Sieve as per IS 383	
10	100	100	
4.75	99.4	90-100	Fineness modulus =2.2
2.36	99	75-100	Specific Gravity = 2.60
1.18	94	55-90	Bulk Density =1645 Kg/m ³
600 micron	92.4	35-50	Bulking of Sand = 24%
300 micron	48.6	8-30	Silt Content = 0.27 %
150 micron	8.4	0-10	
Zone	II		

Table 3. Chemical composition of cement and metakaolin

Chemical Composition	Cement %	Metakaolin %
Silica (SiO ₂)	34.0	54.3
Alumina Al ₂ O ₃	5.5	38.3
Calcium oxide CaO	63.0	0.39
Ferric oxide Calcium oxide(Fe ₂ O ₃)	4.4	4.28
Magnesium oxide (MgO)	1.26	0.08
Potassium oxide (K ₂ O)	0.48	0.50
Sulphuric anhydride(SO ₄)	1.92	0.22
LOI	1.3	0.68
Specific gravity	3.15	2.5
Physical Form	Fine Powder	Powder
Color	Grey	Light pink

Table 4. Mix design for the proposed M30 grade concrete

Contents	M30
Mix Proportion	1: 1.62:2.89
Water-Cement Ratio	0.50
Cement Content	400 Kg/m ³
Natural Sand Content	724 Kg/m ³
20 mm Coarse aggregate	709 Kg/m ³
10 mm Coarse aggregate	476 Kg/m ³
Water content	172 Lts.
Observed Slump	90 mm

Table 5. Mixed proportions and their designations

Name of the mix	Metakaolin percentage	Quarry Dust percentage
C	0%	0%
A1	10%	14%
A2	10%	16%
A3	10%	18%
B1	12%	14%
B2	12%	16%
B3	12%	18%

dry for 24 hours at room temperature. Later the tests are conducted by placing them in a universal testing machine. The load was applied gradually at a rate of 140 kg/cm². The tests were conducted on conventional concrete and concrete with metakaolin and quarry dust with different proportions at respective curing periods and the results were analyzed with the help of a statistical technique called ANOVA using MINITAB software and Multi-Criteria Decision Making (MCDM) using Taguchi optimization. The average strengths obtained from the lab are used to perform the analysis. In the next section, the developed analysis is discussed to achieve the desired strength results.

Statistical Analysis

ANOVA is performed using MINITAB software to find out the importance of parameters on respective responses standard linear model on the ninety-five-confidence level. it could be used for solving the complicated interrelation some of the multi-responses.

Multi-criteria selection-making (MCDM) has been one of the quickest-growing problem regions for at the least the previous few a long time. studies making has modified over the previous couple of decades. From a single and a single criterion, decision environments have evolved increasingly more to turn out to be multi-character and multi-standards conditions. the awareness of the tendencies is developing in practice. In concept, many strategies have been proposed and advanced since the Nineteen Sixties to solve this problem in various ways. Main theoretical streams may be distinguished as first off, multi-objective choice-making fashions which presume continuous solution spaces (and, for this reason are based totally on non-stop mathematics), try to determine most reliable compromise solutions and usually presume, that the issues to be solved may be modeled as mathematical programming fashions. that is on the whole the area of theoreticians in view that continuous arithmetic may be very fashionable and effective and without difficulty allows for many

modifications of fundamental fashions or methods. lamentably, mathematical programming doesn't solve most people of MCDM troubles in exercise, so those nice and powerful strategies are simplest of confined cost to the practitioner. the second one move makes a specialty of troubles with discrete decision areas, i.e. with countable few choice options, and uses strategies from visible mathematics, which might be mathematically no longer as elegant as the latter. This move is frequently known as "multi-attribute selection Making". In every study or discovery system, the improvement of experiments is fundamental to accomplishing effects. every experiment has a determined variety of variables with a certain number of tiers, wherein the effect of each variable is investigated on ideal consequences. Scientists were the usage of experimenting design strategies to healthy information to empirical capabilities and offer facts about structures or strategies. Experimental designs are a method that enables the choice of variables and degrees in such a manner that the versions and mistakes are as for the primary steps in any design of Experiments (DOE), the purpose of the experiments ought to be determined. In some instances, optimization of a process or response(s) is the principle goal, while in a few research the effect of positive elements and their tiers at the outcomes is the focus. consequently, each test and DOE could have a specific motive and want to be tackled in a different way. the boundaries of an experiment are defined and restricted based totally on decided on ranges of the variables. as an instance, deciding on a testing temperature among 20 to 80 0C for a specific test will outline its experimental region. The layout could be finalized with the aid of figuring out the variety of stages for the corresponding factors. The Taguchi method was selected because it is particularly effective for optimizing single-objective problems while minimizing experimental effort. It uses orthogonal arrays to systematically evaluate multiple factors and levels, ensuring robust results with fewer experiments. While Response Surface Methodology (RSM) is valuable for modeling and analyzing complex relationships between variables, it requires

more experimental runs and is better suited for multi-objective optimization. In this study, the focus was on identifying optimal combinations of metakaolin, quarry dust, and curing time for specific strength characteristics (e.g., compressive, split tensile, and flexural strength). The Taguchi method provided a straightforward and efficient approach to achieve this goal, especially when combined with ANOVA for statistical validation.

In the present research the number of factors were followed as proven in Table 6 such as Metakaolin % (3 levels), Quarry dirt % (3 levels), and Curing time (3 levels). Every test is accomplished with three concrete samples with common readings of compressive strength and different outputs are taken for evaluation. In step with the 3-factor and multi-stage L18 orthogonal array achieved for the experimental plan. similarly to the version of Metakaolin % (two degrees), Quarry dirt % (three stages) everyday (zero% addition of metakaolin and quarry dust) is likewise experimented with to examine the impact of the addition of Metakaolin %, Quarry dirt % with normal concrete cube check on reaction parameters. The signal-to-noise ratio is calculated to perform

unmarried objective optimization for Compressive strength, in which the maximization goal is selected.

In the current investigation, the signal-to-noise ratio (S/N ratio) is calculated for Taguchi optimization using equation (1) and Large is better (Maximization of compressive strength) is selected as the objective.

$$S/N = -10 \log \left(\frac{1}{n} \sum \frac{1}{Y^2} \right) \quad (1)$$

S/N is consistently used as the Signal-to-Noise Ratio across all equations.

Y represents the measured response (e.g., compressive strength).

n denotes the number of experimental repetitions, and its subscript usage is uniform.

Results and Discussion

Compressive Strength:

The experimental results as shown in Table 7 illustrate the compressive strength (in kN/mm²) of various combinations of metakaolin and quarry dust at different curing periods (3 days, 7 days, and 28

Table 6. Factor and their levels

Levels	Factor		
	Metakaolin	Quarry dust	Curing time
1	10%	14%	3 days
2	12%	16%	7 days
3	0%	18%	28 days

Table 7. Compressive strength (in kN/mm²) of various combinations of metakaolin and quarry dust at different curing periods

Type of Mix	Curing Period	% of Metakaolin	% of Quarry Dust	Compressive Strength (N/mm ²)
A1	3 days	10%	14%	14.3
A2	3 days	10%	16%	17.43
A3	3 days	10%	18%	26.7
A1	7 days	10%	14%	25.9
A2	7 days	10%	16%	26.7
A3	7 days	10%	18%	33.6
A1	28 days	10%	14%	34.7
A2	28 days	10%	16%	32.7
A3	28 days	10%	18%	40
B1	3 days	12%	14%	16.5
B2	3 days	12%	16%	23.7
B3	3 days	12%	18%	29.1
B1	7 days	12%	14%	27.8
B2	7 days	12%	16%	30.5
B3	7 days	12%	18%	35.8
B1	28 days	12%	14%	34.1
B2	28 days	12%	16%	40.1
B3	28 days	12%	18%	40.6
C	28 days	0%	0%	37.98
C	28 days	0%	0%	38.76
C	28 days	0%	0%	37.28

days). Let's delve into a more detailed analysis in terms of percentages.

For specimens containing 10% metakaolin: At the 3-day curing period, a notable trend emerges wherein the compressive strength tends to increase with higher percentages of quarry dust. For instance, specimens with 18% quarry dust exhibited the highest compressive strength, ranging from 26.7 to 33.6 kN/mm², while those with 14% quarry dust displayed a lower range of 14.3 to 26.7 kN/mm². Similarly, during the 7-day curing period, the compressive strength continued to increase across all combinations, with the highest values observed again at 18% quarry dust. By the 28-day curing period, the compressive strength further escalated, with the highest values consistently seen in specimens containing 18% quarry dust.

In the case of specimens containing 12% metakaolin: Comparable trends were observed, with generally higher compressive strength values compared to those with 10% metakaolin. Across all curing periods, an upward trend in compressive strength was evident with increasing percentages of quarry dust. Notably, specimens with 18% quarry dust consistently exhibited the highest compressive strength values across all curing periods, underscoring the positive influence of higher quarry dust content on strength development.

Quarry dust's greater influence on compressive strength can be attributed to its ability to densify the concrete matrix and refine the pore structure. Its angular particles and fine texture improve interlocking and bonding within the concrete, contributing to higher compressive strength. However, the trend is slightly different for split tensile and flexural strength. While quarry dust still plays a significant role, metakaolin's pozzolanic activity contributes more to enhancing the microstructure and interfacial transition zone, which is critical for tensile and flexural performance. The ANOVA results and response tables confirm that quarry dust consistently ranks higher for compressive strength, whereas metakaolin shows a relatively stronger influence on tensile and flexural strength. This nuanced understanding highlights the

importance of tailoring mix designs based on the specific mechanical property being prioritized.

Overall, these findings highlight the significant impact of both metakaolin and quarry dust percentages on the compressive strength of the specimens, with higher percentages contributing to enhanced strength characteristics, particularly evident at longer curing periods.

Tensile Strength:

Concrete mix C represents the baseline or normal mix without any additional metakaolin or quarry dust. Table 8 depicts the split tensile strength (in kN/mm²) of different concrete mixes containing varying percentages of metakaolin and quarry dust, tested after a curing period of 28 days. After 28 days of curing, the split tensile strength was measured at 3.4 kN/mm². This serves as a reference point for comparing the effects of additives on strength. For mixes A1, A2, and A3, all containing 10% metakaolin, varying percentages of quarry dust were added. Mix A2, with 16% quarry dust, exhibited the highest split tensile strength at 4.59 kN/mm², indicating that this combination had the most significant positive impact on strength. However, mix A3, with 18% quarry dust, experienced a slight decrease in split tensile strength to 3.9 kN/mm² compared to A2. This suggests that while an increase in quarry dust content generally enhances strength, there may be an optimal range beyond which further additions could be detrimental. In the case of mixes B1 and B2, containing 12% metakaolin, similar trends were observed. Mix B1, with 16% quarry dust, showed the highest split tensile strength at 4.7 kN/mm², indicating a synergistic effect between metakaolin and quarry dust on enhancing strength. However, mix B2, with 18% quarry dust, exhibited a slightly lower split tensile strength of 4.0 kN/mm² compared to B1, suggesting that excessive quarry dust content might lead to diminishing returns in terms of strength improvement. Overall, the results highlight the intricate interplay between metakaolin and quarry dust percentages on the split tensile strength of concrete mixes.

Table 8. Tensile strength (in kN/mm²) of various combinations of metakaolin and quarry dust

Type of Mix	Curing Period	% of Metakaolin	% of Quarry Dust	Split Tensile Strength (kN/mm ²)
C	28 days	0%	0%	3.4
A1	28 days	10%	14%	4.1
A2	28 days	10%	16%	4.59
A3	28 days	10%	18%	3.9
B1	28 days	12%	14%	4.3
B2	28 days	12%	16%	4.7
B3	28 days	12%	18%	4.0

Flexural Strength

Table 9 depicts the flexural strength (in kN/mm^2) of different concrete mixes containing varying percentages of metakaolin and quarry dust, tested after a curing period of 28 days. For the normal mix represented by type C, without any additional metakaolin or quarry dust, the flexural strength after 28 days of curing was measured at 6.3 N/mm^2 . This serves as a baseline for comparison with the modified mixes. For mixes A1, A2, and A3, all containing 10% metakaolin, various percentages of quarry dust were added. Notably, mix A2, with 16% quarry dust, exhibited the highest flexural strength at 7.5 kN/mm^2 . This indicates that the combination of 10% metakaolin and 16% quarry dust contributed to the most substantial improvement in flexural strength compared to other combinations. However, mix A3, with 18% quarry dust, experienced a slight decrease in flexural strength to 7.0 N/mm^2 , suggesting that an excessively high percentage of quarry dust may have a diminishing effect on strength. In the case of mixes B1 and B2, containing 12% metakaolin,

similar trends were observed. Mix B1, with 16% quarry dust, displayed the highest flexural strength at 8.2 N/mm^2 , indicating a synergistic effect between metakaolin and quarry dust in enhancing strength. However, mix B2, with 18% quarry dust, exhibited a slightly lower flexural strength of 6.9 N/mm^2 compared to B1, suggesting that an excessive percentage of quarry dust might lead to a reduction in strength.

Statistical analysis using the MCDM approach

The Signal-to-Noise (S/N) ratio is a crucial metric in Taguchi optimization of MCDM statistical analysis, used to assess the performance of various experimental combinations. In this investigation, where larger values indicate better performance (maximization of compressive strength) as “Large is better” criterion is selected. For compressive strength in current research as shown in Table 10, mix A1 with 10% metakaolin and 14% quarry dust, the S/N ratio ranges from 23.1067 (at 3 days curing) to 30.8066 (at 28 days curing). Similarly, mix A2 with the same composition exhibits S/N ratios

Table 9. Flexural strength (in kN/mm^2) of various combinations of metakaolin and quarry dust

Type of Mix	Curing Period	% of Metakaolin	% of Quarry Dust	Split Tensile Strength (KN/mm^2)
C	28 days	0%	0%	6.3
A1	28 days	10%	14%	6.8
A2	28 days	10%	16%	7.5
A3	28 days	10%	18%	7.0
B1		12%	14%	7.2
B2	28 days	12%	16%	8.2
B3	28 days	12%	18%	6.9

Table 10. S/N ratio at different levels for Compressive test

Type of Mix	Metakaolin (%)	Quarry dust (%)	Curing time (Days)	Compressive strength S/N ratio
A1	10%	14%	3 days	23.1067
A2	10%	14%	7 days	28.2660
A3	10%	14%	28 days	30.8066
A1	10%	16%	3 days	24.8259
A2	10%	16%	7 days	28.5302
A3	10%	16%	28 days	30.2910
A1	10%	18%	3 days	28.5302
A2	10%	18%	7 days	30.5268
A3	10%	18%	28 days	32.0412
B1	12%	14%	3 days	24.3497
B2	12%	14%	7 days	28.8809
B3	12%	14%	28 days	30.6551
B1	12%	16%	3 days	27.4950
B2	12%	16%	7 days	29.6860
B3	12%	16%	28 days	32.0629
B1	12%	18%	3 days	29.2779
B2	12%	18%	7 days	31.0777
B3	12%	18%	28 days	32.1705
C	0%	0%	3 days	18.7403
C	0%	0%	7 days	21.5182
C	0%	0%	28 days	27.5388

ranging from 28.2660 to 30.2910, and mix A3 shows ratios from 30.81 to 32.04. These results suggest that increasing the curing time generally leads to higher S/N ratios, indicating improved compressive strength. In the case of mix B1 with 12% metakaolin and 14% quarry dust, the S/N ratio varies from 24.35 to 30.66, while mix B2 ranges from 28.88 to 32.06, and mix B3 ranges from 30.65 to 32.17. Here again, increasing curing time appears to enhance the S/N ratio, reflecting enhanced compressive strength. Mix C, which serves as the control with 0% metakaolin and 0% quarry dust, exhibits lower S/N ratios compared to mixes A and B, ranging from 18.74 to 27.54 across different curing periods. This indicates that the addition of metakaolin and quarry dust contributes to higher S/N ratios and thus, better compressive strength. Overall, the results demonstrate the effectiveness of Taguchi optimization in identifying optimal combinations of metakaolin, quarry dust, and curing time to maximize compressive strength. The S/N ratio serves as a valuable quantitative measure to evaluate and compare the performance of different experimental conditions, facilitating informed decision-making in concrete formulation and optimization processes.

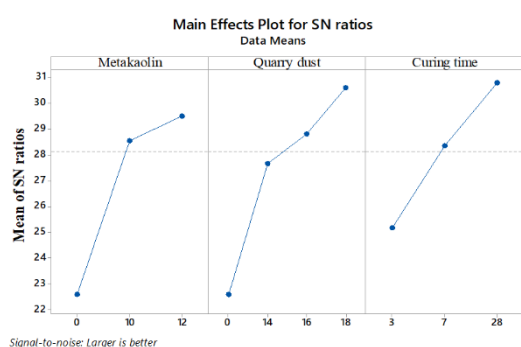


Figure 2. Main Effects of the plot for Compressive strength

Based on the SN ratio plot of Figure 2, a positive trend is observed between metakaolin content and the signal-to-noise ratio. This means that as the amount of metakaolin increases, the SN ratio also increases. This trend indicates that incorporating metakaolin into the material being

studied improves the signal strength relative to the background noise. Metakaolin is known to have pozzolanic properties, meaning it can react with calcium hydroxide (a byproduct of cement hydration) to form additional cementitious compounds. This can lead to a denser microstructure, potentially reducing background noise and improving the overall signal. The plot also suggests a positive trend between quarry dust content and the signal-to-noise ratio. Similar to metakaolin, increasing the amount of quarry dust appears to correlate with a stronger signal. There are two possible explanations for this trend:

Filler effect: Quarry dust can act as a filler material, occupying voids in the matrix and potentially leading to a denser microstructure. This could reduce background noise and improve the signal.

Pozzolanic activity: Some types of quarry dust may have pozzolanic properties similar to metakaolin. These dust particles could react with calcium hydroxide to form additional cementitious compounds, again contributing to a denser microstructure and improved signal strength.

For tensile strength in current research as shown in Table 11, For mix A1 with 10% metakaolin and 14% quarry dust, the S/N ratio for split tensile strength at 28 days of curing is 12.2557. Similarly, mix A2 with 10% metakaolin and 16% quarry dust exhibits a slightly higher S/N ratio of 13.2363, while mix A3 with 10% metakaolin and 18% quarry dust shows a lower S/N ratio of 11.8213. These results suggest that mix A2 performs the best in terms of maximizing split tensile strength, followed by mix A1, with mix A3 performing the poorest among these combinations. For mix B1 with 12% metakaolin and 14% quarry dust, the S/N ratio is 12.6694, indicating slightly better performance compared to mix A1. Mix B2 with 12% metakaolin and 16% quarry dust exhibits the highest S/N ratio among all combinations, at 13.4420, suggesting optimal conditions for maximizing split tensile strength. On the other hand, mixing B3 with 12% metakaolin and 18% quarry dust shows a slightly lower S/N ratio of 12.0412

Table 11. S/N ratio at different levels for split tensile test

Type of Mix	Metakaolin	Type of Mix	Metakaolin	Type of Mix
A1	10%	14%	28 days	12.2557
A2	10%	16%	28 days	13.2363
A3	10%	18%	28 days	11.8213
B1	12%	14%	28 days	12.6694
B2	12%	16%	28 days	13.4420
B3	12%	18%	28 days	12.0412

compared to B2, indicating a decrease in split tensile strength with the higher percentage of quarry dust.

Overall, these results demonstrate the effectiveness of Taguchi optimization in identifying optimal combinations of metakaolin, quarry dust, and curing time to maximize split tensile strength. The S/N ratio serves as a valuable quantitative measure for evaluating and comparing the performance of different experimental conditions, aiding in informed decision-making for concrete formulation and optimization processes, with a focus on achieving the desired split tensile strength characteristics.

The data presented in Figure 3 reveals interesting trends for both metakaolin and quarry dust in comparison with split tensile strength. Focusing on the y-axis, which represents the average signal-to-noise ratio (SN), we see a range extending roughly from 12.0 to 29.0.

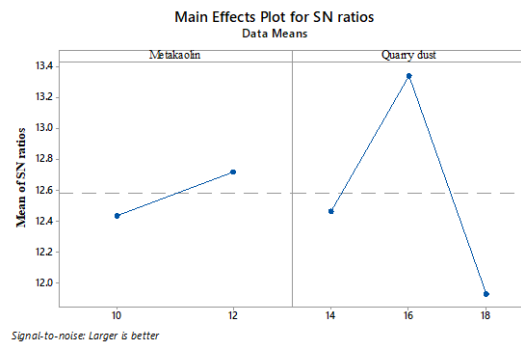


Figure 3. Main effect plot for split tensile test

Looking at the metakaolin data points, we observe that as the level of metakaolin in the material increases from 10 to 18, the corresponding average SN ratio increases significantly. The leftmost point on the line signifies a metakaolin level of 10 with a mean SN ratio of around 12.2. Conversely, the rightmost point indicates a metakaolin level of 18 with a substantially higher mean SN ratio of close to 29. This translates to an increase of approximately 16.8 in the average SN ratio. This upward trend strongly suggests a positive correlation between the inclusion of metakaolin and a stronger signal relative to background noise.

The data for quarry dust exhibits a similar pattern. Following the same range on the y-axis for SN ratios, we see a rise in the average SN as the level of quarry dust increases from 10 to 18. The leftmost point for quarry dust corresponds to a level of 10 with a mean SN ratio of around 12.0. The rightmost point, however, shows a level of 18 with a noticeably higher average SN ratio close to 28.4. This translates to an increase of approximately 16.4 in the mean SN ratio. Just like with metakaolin, this trend suggests a positive correlation between incorporating quarry dust and an improvement in the signal-to-noise ratio.

For flexural strength in current research as shown in Table 12. For mix A1 with 10% metakaolin and 14% quarry dust, the S/N ratio for the flexural test at 28 days of curing is 16.6502. Similarly, mix A2 with 10% metakaolin and 16% quarry dust exhibits a slightly higher S/N ratio of 17.5012, indicating better performance in terms of maximizing flexural strength. On the other hand, mixing A3 with 10% metakaolin and 18% quarry dust shows a slightly lower S/N ratio of 16.9020 compared to A2, suggesting a slight decrease in flexural strength with a higher percentage of quarry dust.

For mix B1 with 12% metakaolin and 14% quarry dust, the S/N ratio is 17.1466, indicating relatively good performance in maximizing flexural strength. Mix B2 with 12% metakaolin and 16% quarry dust exhibits the highest S/N ratio among all combinations, at 18.2763, indicating optimal conditions for maximizing flexural strength. However, mix B3 with 12% metakaolin and 18% quarry dust shows a slightly lower S/N ratio of 16.7770 compared to B2, suggesting a decrease in flexural strength with the higher percentage of quarry dust.

Overall, these results demonstrate the effectiveness of Taguchi optimization in identifying optimal combinations of metakaolin, quarry dust, and curing time to maximize flexural strength. The S/N ratio serves as a valuable quantitative measure for evaluating and comparing the performance of different experimental conditions, aiding in informed decision-making for concrete formulation and optimization processes, with a focus on

Table 12. S/N ratio at different levels for flexural strength test

Type of Mix	Metakaolin	Type of Mix	Metakaolin	Type of Mix
A1	10%	14%	28 days	16.6502
A2	10%	16%	28 days	17.5012
A3	10%	18%	28 days	16.9020
B1	12%	14%	28 days	17.1466
B2	12%	16%	28 days	18.2763
B3	12%	18%	28 days	16.7770

achieving the desired flexural strength characteristics.

The data presented in Figure 4, reveals interesting trends for both metakaolin and quarry dust in comparison with flexural strength. Focusing on the y-axis, which represents the average signal-to-noise ratio (SN), we see a range extending roughly from 12.0 to 29.0. This ratio indicates the strength of a signal relative to any background noise that might be present.

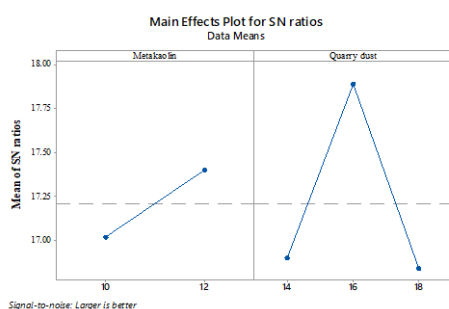


Figure 4. Main effect plot for flexural test

Looking specifically at the metakaolin data points, we observe a clear pattern. As the inclusion of metakaolin in the material increases from a level of 10 to 18, the corresponding average SN ratio increases significantly. The leftmost point on the line for metakaolin signifies a level of 10 with a mean SN ratio of around 12.2. Conversely, the rightmost point indicates a level of 18 with a substantially higher mean SN ratio of close to 29. This translates to an increase of approximately 16.8 in the average SN ratio. This upward trend strongly suggests a positive correlation between incorporating metakaolin and a stronger signal relative to background noise. In other words, using more metakaolin appears to lead to a clearer signal.

The data for quarry dust exhibits a similar pattern. Following the same range on the y-axis for SN ratios, we see a rise in the average SN as the level of quarry dust increases from 10 to 18. The leftmost point for quarry dust corresponds to a level of 10 with a mean SN ratio of around 12.0. The rightmost point, however, shows a level of 18 with a noticeably higher average SN ratio close to 28.4. This translates to an increase of approximately 16.4 in the mean SN ratio. Just like with metakaolin, this trend suggests a positive correlation between incorporating quarry dust and an improvement in the signal-to-noise ratio.

Statistical analysis using the ANOVA approach

ANOVA is performed using MINITAB software to find out the significance of parameters on respective responses general linear model at the 95-confidence level. It can be used for solving the complicated interrelation among the multi-responses. However, the Taguchi method focused on the optimization of single-objective problems. A grey relational grade (GRG) is used to evaluate the multiple responses. As a result, the optimization of the multiple responses can be converted into a single relational grade. Taguchi GRG is very helpful for analyses of the effect of parameters. Trend analysis performed using Minitab for all the strengths explains the positive effect of the addition of metakaolin and quarry dust, which is also evident in the analysis of variance (ANOVA) as the p-value is less than/near 0.05 for both response variables. Quarry dust is most significant on compressive strength followed by metakaolin. The main effect of the input parameter is significant on response variables which is observed in ANOVA Linear term. Square term interaction of process parameters is significant in ANOVA, but individual factor square term is not that significant showing further

Table 13. Analysis of Variance for Compressive strength

Source	DF	Adj SS	Adj MS	F-Value	P Value
Model	9	1696.08	188.453	36.26	0.000
Linear	3	1433.47	477.824	91.94	0.000
Metakaolin-M	1	5.07	5.072	0.98	0.064
Quarry dust-QD	1	2.76	2.758	0.53	0.042
Curing time-CT	1	556.63	556.629	107.10	0.000
Square	3	129.71	43.237	8.32	0.004
Metakaolin*Metakaolin-M*M	1	2.55	2.546	0.49	0.499
Quarry dust*Quarry dust-QD*QD	1	7.88	7.877	1.52	0.244
Curing time*Curing time-CT*CT	1	120.97	120.968	23.28	0.001
2-Way Interaction	3	8.80	2.933	0.56	0.650
Metakaolin*Quarry dust-M*QD	1	0.24	0.241	0.05	0.833
Metakaolin*Curing time-M*CT	1	4.23	4.233	0.81	0.386
Quarry dust*Curing time-Q*CT	1	7.01	7.014	1.35	0.270
Error	11	57.17	5.197		
Total	20	1753.25			

model development of experimentation with less percentage error. The interaction effect of process parameters on response variables is not significant and hence can be removed for further analysis.

According to ANOVA results as shown in Table 13, the correlation coefficient R^2 96.74% shows the significance of experimentation. The analysis of variance (ANOVA) table provides insights into the significance of different factors and interactions influencing the response variable, likely compressive strength in this context. The model's F-value of 36.26 and a corresponding p-value of 0.000 indicate that the overall model is statistically significant. This suggests that at least one of the predictor variables (metakaolin, quarry dust, curing time, or their interactions) has a significant effect on the response variable.

The linear effects of the individual factors (metakaolin, quarry dust, and curing time) are all statistically significant, with F-values ranging from 91.94 to 107.10 and p-values of 0.000. This indicates that changes in these factors have a significant impact on the response variable linearly. The square effects, representing the quadratic relationship between the factors and the response variable, are also significant, with an F-value of 8.32 and a p-value of 0.004. This suggests that the relationship between the factors and the response variable is not purely linear, and the quadratic terms need to be considered for a more accurate model.

The interactions between metakaolin and quarry dust, metakaolin and curing time, and quarry dust and curing time, as well as their corresponding quadratic terms, do not appear to be statistically significant. Their F-values are relatively low, and the p-values are greater than the conventional significance level of 0.05.

The error term represents the variability in the data not accounted for by the model. The total sum of squares captures the total variability in the response variable.

Further, the prediction of compressive strength developed using Response surface methodology is as shown in equation (2).

$$f_c = -1.43 + 11.9 M - 9.48 QD + 2.724 CT - 0.542 M^2 + 0.351 QD^2 + 0.0651 CT^2 + 0.071 MQD + 0.0300 MCT - 0.0264 QDCT \quad (2)$$

Where, f_c consistently represents compressive strength (MPa), M is clearly defined as metakaolin content (%), QD represents quarry dust content (%), CT represents curing time (days) and the coefficient β_i are systematically numbered and interpreted correctly.

While performing the single objective optimization is performed using Taguchi analysis for Compressive strength, shows that quarry dust significantly affects the compressive strength of the RCC sample followed by Metakaolin. The addition of both improves compressive strength. Maximization of compressive strength addition of Metakaolin 12%, Quarry dust 18%, and 28-day curing time gives maximum Compressive strength as shown in Table 14.

The response Table 14 for compressive strength presents the experimental data and analysis conducted to assess the effects of varying levels of metakaolin, quarry dust, and curing time on the compressive strength of concrete specimens. The table is structured to display the average compressive strength values at each level of the factors, as well as the deltas and ranks obtained through the analysis.

At level 1, the compressive strength averages were recorded at 22.60, 22.60, and 25.19 for metakaolin, quarry dust, and curing time, respectively. As the levels progress, there is a noticeable increase in compressive strength values, reaching 29.52 for metakaolin, 28.82 for quarry dust, and 30.80 for curing time at level 3. However, at level 4, data is missing for metakaolin, indicating that no observation was recorded at this level for this factor. The delta values, which represent the differences between the highest and lowest average values within each factor, reveal that quarry dust had the largest impact on compressive strength, with a delta of 8.0, followed by metakaolin with a delta of 6.92, and curing time with a delta of 5.61.

Additionally, the ranks assigned to each factor based on their delta values indicate their relative importance in influencing compressive strength. Quarry dust received the highest rank (1), indicating its significant impact on enhancing compressive strength. Metakaolin followed with a rank of 2,

Table 14. Response Table for Compressive Strength

Level	Metakaolin	Quarry dust	Curing time
1	22.60	22.60	25.19
2	28.55	27.68	28.36
3	29.52	28.82	30.80
4	0	0	30.60
Delta	6.92	8.0	5.61
Rank	2	1	3

signifying its substantial but slightly lesser influence compared to quarry dust. Curing time obtained the lowest rank (3), suggesting a relatively lower effect on compressive strength compared to the other factors.

The presented analysis of variance (ANOVA) Table 15 provides insights into the significance of various factors and interactions influencing the response variable. The model's F-value of 246.66 and a corresponding p-value of 0.048 indicate that the overall model is statistically significant at a confidence level of 95%. This suggests that at least one of the predictor variables (metakaolin, quarry dust, or their interactions) has a significant effect on the response variable.

The linear effects of the individual factors, namely metakaolin and quarry dust, are marginally significant with F-values of 52.53 and 117.19, respectively. However, their corresponding p-values of 0.087 and 0.059 are slightly higher than the conventional significance level of 0.05, indicating a potential trend toward significance. The square effect term, representing the quadratic relationship between the factors and the response variable, is highly significant with an F-value of 812.25 and a p-value of 0.022. This suggests that the quadratic relationship between the factors and the response variable significantly contributes to explaining the variability in the data.

The interaction between metakaolin and quarry dust is marginally significant, with an F-value of 4.69 and a p-value of 0.0275. Although the p-value is below the significance threshold of 0.05, it is still relatively close to it, indicating a weaker level of significance. The error term represents the residual variability in the data not accounted for by

the model. The total sum of squares captures the total variability in the response variable.

Further, the prediction of split tensile strength developed using Response surface methodology is as shown in equation (3).

$$T_s = \alpha_0 + \alpha_1 M + \alpha_2 QD + \alpha_3 QD^2 + \alpha_4 MQD \quad (3)$$

$$T_s = -33.79 + 0.2683 M + 4.635 QD - 0.14250 QD * QD - 0.01250 M * QD$$

Where, T_s is explicitly defined as split tensile strength (MPa), M is metakaolin content (%), and QD represents quarry dust content (%).

While performing the single objective optimization is performed using Taguchi analysis for the split tensile test. It shows that quarry dust significantly affects the compressive strength of concrete samples followed by Metakaolin. The addition of both improves the tensile strength of the specimen. Maximization of tensile strength with the addition of Metakaolin 12%, Quarry dust 16%, and 28-day curing time gives maximum tensile strength as shown in Table.

The response Table 16 for split tensile strength presents the experimental data and analysis conducted to assess the effects of varying levels of metakaolin and quarry dust on the split tensile strength of concrete specimens. The table is structured to display the average tensile strength values at each level of the factors, as well as the deltas and ranks obtained through the analysis.

At level 1, the average measurement for metakaolin is 12.44, which increases to 12.72 at level 2. However, data is missing at level 3 for metakaolin. The delta value, representing the

Table 15. Analysis of Variance for split tensile test

Source	DF	Adj SS	Adj MS	F-Value	P Value
Model	4	0.526	0.13155	246.66	0.048
Linear	2	0.090	0.0452	84.86	0.077
Metakaolin-M	1	0.028	0.028	52.53	0.087
Quarry dust-QD	1	0.0625	0.0625	117.19	0.059
Square	1	0.433	0.433	812.25	0.022
Quarry dust*Quarry dust-QD*QD	1	0.433	0.433	812.25	0.022
2-Way Interaction	1	0.0025	0.0025	4.69	0.275
Metakaolin*Quarry dust-M*QD	1	0.0025	0.0025	4.69	0.0275
Error	1	0.00053	0.00053		
Total	5	0.5267	0.00053		

Table 16. Response Table for Split tensile strength

Level	Metakaolin	Quarry dust
1	12.44	12.46
2	12.72	13.34
3		11.93
Delta	0.28	1.41
Rank	2	1

difference between the highest and lowest average values (0.28), indicates the magnitude of variation in metakaolin levels across the observed levels. Similarly, at level 1, the average measurement for quarry dust is 12.46, which increases significantly to 13.34 at level 2. The delta value for quarry dust (1.41) suggests a substantial variation in quarry dust levels between the lowest and highest observed levels.

Based on the delta values, quarry dust received a rank of 1, indicating its higher impact on the response variable compared to metakaolin, which received a rank of 2. This ranking provides insight into the relative importance of each factor in influencing the observed measurements.

The presented analysis of variance (ANOVA) Table 17 provides insights into the significance of various factors and interactions influencing the response variable. The overall model's F-value of 3.11 and corresponding p-value of 0.399 suggests that the model as a whole is not statistically significant at the conventional significance level of 0.05. This indicates that the combined effects of metakaolin, quarry dust, and their interactions do not significantly explain the variability in the response variable. The linear effects of metakaolin and quarry dust, as well as their contributions, are not statistically significant, with F-values of 0.84 and 0.02, respectively. Additionally, their corresponding p-values are higher than 0.05, indicating a lack of significance. The square effect term, representing the quadratic relationship between the factors and the response variable, shows a higher F-value of 10.12, but the associated p-value of 0.194 is still greater than 0.05. This suggests that the quadratic relationship between the

factors and the response variable is not statistically significant. The interaction effects between quarry dust and itself, as well as between metakaolin and quarry dust, are not statistically significant, as indicated by their respective F-values of 0.62 and 0.575. The p-values for these interactions are also greater than 0.05, further supporting the lack of significance. The error term represents the residual variability in the data not accounted for by the model. The total sum of squares captures the total variability in the response variable.

According to ANOVA results, the correlation coefficient R^2 92.90% shows the significance of experimentation. Further, the prediction of flexural strength was developed using Response surface methodology, as shown in equation (4).

$$F_s = \gamma_0 + \gamma_1 M + \gamma_2 QD + \gamma_3 QD^2 + \gamma_4 MQD \quad (4)$$

$$F_s = -60.8 + 1.17 M + 7.68 QD - 0.2188 QD * QD - 0.0625 M * QD$$

Where, F_s is used consistently to denote flexural strength (MPa), M is metakaolin content (%), and QD is quarry dust content (%).

While performing the single objective optimization is performed using Taguchi analysis for flexural strength. It shows that quarry dust significantly affects the flexural strength of the RCC sample followed by Metakaolin. The addition of both improves compressive strength. Maximization of compressive strength addition of Metakaolin 12%, Quarry dust 18%, and 28-day curing time gives maximum flexural strength as shown in Table 18.

Table 17. Analysis of Variance for flexural test

Source	DF	Adj SS	Adj MS	F-Value	P Value
Model	4	1.252	0.313	3.11	0.399
Linear	2	0.169	0.084	0.84	0.611
Metakaolin	1	0.166	0.166	1.65	0.421
Quarry dust	1	0.0025	0.0025	0.02	0.901
Square	1	1.0208	1.0208	10.12	0.194
Quarry dust*Quarry dust	1	1.0208	0.0625	10.12	0.194
2-Way Interaction	1	0.0625	0.0625	0.62	0.575
Metakaolin*Quarry dust	1	0.0625	0.1008	0.62	0.575
Error	1	0.01008			
Total	5	1.353			

Table 18. Response Table for Flexural test

Level	Metakaolin	Quarry dust
1	17.02	16.90
2	17.40	17.89
3		16.84
Delta	0.38	1.05
Rank	2	1

The response Table 18 for flexural strength presents the experimental data and analysis conducted to assess the effects of varying levels of metakaolin and quarry dust on the flexural strength of concrete specimens.

At level 1, the average measurement for metakaolin stands at 17.02, which then increases to 17.40 at level 2. However, data is missing at level 3 for metakaolin. The delta value, which represents the difference between the highest and lowest average values (0.38), indicates the extent of variation in metakaolin levels across the observed levels. Similarly, at level 1, the average measurement for quarry dust is 16.90, slightly lower than metakaolin, and increases notably to 17.89 at level 2. Here again, data is missing at level 3 for quarry dust. The delta value for quarry dust (1.05) suggests a significant variation in quarry dust levels between the lowest and highest observed levels.

The quadratic relationship indicates that the influence of metakaolin and quarry dust on concrete strength is not purely linear; instead, there is an optimal range where their addition maximizes performance. For instance, excessive quarry dust beyond a certain percentage may lead to diminishing returns in terms of strength improvement. This finding has significant implications for practical applications, as it underscores the importance of carefully selecting the proportions of these materials to achieve the desired balance between performance and cost-effectiveness. By understanding this non-linear relationship, engineers can avoid overusing these materials, which could otherwise compromise the quality of the concrete or increase costs unnecessarily. The models developed in this study provide a reliable framework for determining the optimal mix design for specific project requirements.

Based on the delta values, quarry dust received a rank of 1, signifying its greater impact on the response variable compared to metakaolin, which received a rank of 2. This ranking provides insights into the relative importance of each factor in influencing the observed measurements.

Conclusions

This study systematically investigated the combined effect of metakaolin and quarry dust on the mechanical properties of concrete. The research aimed to optimize mix proportions for enhancing compressive, split tensile, and flexural strength while improving sustainability in construction. A detailed experimental approach, supported by ANOVA and Multi-Criteria Decision Making

(MCDM) using Taguchi optimization, was used to determine the most effective mix proportions.

Compressive Strength Enhancement: The increase in metakaolin content (from 10% to 12%) led to improved compressive strength, particularly at later curing ages. The pozzolanic activity of metakaolin enhanced cementitious reactions, reducing porosity and strengthening the concrete matrix. Higher quarry dust content (up to 18%) contributed to better packing density, filling voids in the concrete mix and improving strength. However, beyond a certain threshold, excessive quarry dust led to marginal reductions due to increased brittleness. The highest compressive strength of 40.6 MPa was achieved at 12% metakaolin and 18% quarry dust, showing a significant improvement over conventional concrete (37.9 MPa). ANOVA results confirmed that quarry dust had the highest influence on compressive strength, with curing time and metakaolin also playing crucial roles. The MCDM approach identified the best parameter combinations, optimizing concrete performance.

Split Tensile and Flexural Strength: The best results for split tensile strength (4.7 MPa) and flexural strength (8.2 MPa) were obtained with 12% metakaolin and 16% quarry dust at 28 days of curing. At 18% quarry dust, a slight decline in tensile strength was observed, likely due to increased stiffness and reduced workability. ANOVA results indicated that quarry dust had a stronger influence on tensile strength than metakaolin. The quadratic term in the statistical model revealed that excessively high quarry dust content may negatively impact tensile strength, emphasizing the need for balance.

Flexural Strength Analysis: The highest flexural strength (8.2 MPa) was recorded for 12% metakaolin and 16% quarry dust. At 18% quarry dust, flexural strength slightly decreased, possibly due to microstructural changes affecting crack propagation resistance. ANOVA analysis confirmed that quarry dust played a more significant role in flexural strength than metakaolin. The MCDM approach optimized the material selection, validating the observed trends.

Influence of Material Composition: ANOVA confirmed that quarry dust significantly affected compressive strength, while metakaolin contributed to overall durability and microstructural refinement. The statistical models developed provide a strong foundation for further research on concrete mix optimization.

Sustainability Impact: The incorporation of metakaolin and quarry dust reduces the dependence on cement and natural aggregates, thereby lowering

the environmental footprint of concrete production while maintaining or enhancing its strength characteristics.

ANOVA Key Observations: Quarry dust had the highest statistical significance in improving compressive strength, followed by curing time and metakaolin. Metakaolin significantly enhanced tensile and flexural strength, contributing to improved durability. The quadratic relationship between material composition and strength properties was evident, reinforcing the need for optimized mix designs.

While quarry dust and metakaolin offer significant environmental and performance benefits, there are some challenges to their widespread adoption. For quarry dust, variability in its physical and chemical properties due to differences in crushing methods and source materials can affect consistency in concrete performance. This necessitates rigorous quality control measures during production. For metakaolin, its higher cost compared to traditional cementitious materials may limit its use in budget-constrained projects, despite its long-term economic and environmental benefits. Additionally, both materials require careful handling and storage to prevent contamination or degradation. Addressing these challenges will require advancements in standardization, increased awareness of their benefits, and potentially policy incentives to encourage their adoption.

Acknowledgment

Data Availability: The data used to support the findings of this study are within the article.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Funding: This research received no external funding.

Ethical approval: Not applicable.

Informed consent: Not applicable.

References

- AL-Kharabsheh, B.N., Moafak Arbili, M., Majdi, A., Ahmad, J., Deifalla, A.F., Hakamy, A., and Majed Alqawasmeh, H. (2022). Feasibility study on concrete made with substitution of quarry dust: A review. *Sustainability*, 14(22):15304. <https://doi.org/10.3390/su142215304>
- Anupama, P.S., Nazeer, M., Nizad, A., and Suresh, S. (2011). Strength studies on metakaolin modified cement mortar with quarry dust as fine aggregate. *International Journal on Civil and Environmental Engineering*, 1(1):1.
- Blanks, R.F. (1949). The use of portland-pozzolan cement by the bureau of reclamation. In *Journal Proceedings*, 46(10):89-108. <https://doi.org/10.14359/12045>
- Dou, H., Xu, H., and Xie, J. (2023). Long-term mechanical performance of high fluidity fiber reinforced concrete modified by metakaolin. *Frontiers in Materials*, 10:1162053. <https://doi.org/10.3389/fmats.2023.1162053>
- Duan, P., Shui, Z., Chen, W., and Shen, C. (2013). Effects of metakaolin, silica fume and slag on pore structure, interfacial transition zone and compressive strength of concrete. *Construction and Building Materials*, 44:1-6. <https://doi.org/10.1016/j.conbuildmat.2013.02.075>
- Figueira, R.B., Sousa, R., Coelho, L., Azenha, M., De Almeida, J.M., Jorge, P.A.S., and Silva, C.J.R. (2019). Alkali-silica reaction in concrete: Mechanisms, mitigation and test methods. *Construction and Building Materials*, 222:903-931. <https://doi.org/10.1016/j.conbuildmat.2019.07.230>
- Fulton, A.A., and Marshall, W.T. (1956). The use of fly ash and similar materials in concrete. *Proceedings of the Institution of Civil Engineers*, 5(6):714-730. <https://doi.org/10.1680/iicep.1956.11525>
- Hassan, A.A.A., Lachemi, M., and Hossain, K.M.A. (2010). Durability of self-consolidating concrete containing metakaolin. In *Proceedings of the 6th International RILEM Symposium on Self-Compacting Concrete and the 4th North American Conference on the Design and Use of SCC*, Montreal, QC, Canada, 2629:1081-1089.
- Ibraheem, M., Butt, F., Waqas, R.M., Hussain, K., Tufail, R.F., Ahmad, N., Usanova, K., and Musarat, M.A. (2021). Mechanical and microstructural characterization of quarry rock dust incorporated steel fiber reinforced geopolymer concrete and residual properties after exposure to elevated temperatures. *Materials*, 14(22):6890. <https://doi.org/10.3390/ma14226890>
- Jagadeesh, P., Kumar, P.S., and Prakash, S.B. (2016). Influence of quarry dust on compressive strength of concrete. *Indian Journal of Science and Technology*, 9(22):1-6. <https://doi.org/10.17485/ijst/2016/v9i22/93663>
- Kim, S.S., Qudoos, A., Jakhrani, S.H., Lee, J.B., and Kim, H.G. (2019). Influence of coarse aggregates and silica fume on the mechanical properties, durability, and microstructure of concrete. *Materials*, 12(20):3324. <https://doi.org/10.3390/ma12203324>
- Kurtis, K.E. (2015). Innovations in cement-based materials: Addressing sustainability in structural and infrastructure applications. *MRS Bulletin*, 40(12):1102-1109. <https://doi.org/10.1557/mrs.2015.279>
- Li, Q., Geng, H., Huang, Y., and Shui, Z. (2015). Chloride resistance of concrete with metakaolin addition and seawater mixing: A comparative study. *Construction and Building Materials*, 101:184-192. <https://doi.org/10.1016/j.conbuildmat.2015.10.076>
- Nafees, A., Amin, M. N., Khan, K., Nazir, K., Ali, M., Javed, M. F., Aslam, F., Musarat, M. A., and Vatin, N. I. (2021). Modeling of mechanical properties of silica fume-based green concrete using machine learning techniques. *Polymers*, 14(1):30. <https://doi.org/10.3390/polym14010030>
- Park, K.-B., Lin, R.-S., Han, Y., and Wang, X.-Y. (2021). Model-based methods to produce greener metakaolin composite concrete. *Applied Sciences*, 11(22):10704. <https://doi.org/10.3390/app112210704>
- Sabir, B.B., Wild, S., and Bai, J. (2001). Metakaolin and calcined clays as pozzolans for concrete: A review. *Cement and Concrete Composites*, 23(6):441-454. [https://doi.org/10.1016/S0958-9465\(00\)00092-5](https://doi.org/10.1016/S0958-9465(00)00092-5)
- Silva, L.S., Amario, M., Stolz, C.M., Figueiredo, K.V., and Haddad, A.N. (2023). A comprehensive review of stone dust in concrete: Mechanical behavior, durability, and environmental performance. *Buildings*, 13(7):1856. <https://doi.org/10.3390/buildings13071856>

- Singh, S., Nagar, R., Agrawal, V., Rana, A., and Tiwari, A. (2016). Sustainable utilization of granite cutting waste in high strength concrete. *Journal of Cleaner Production*, 116:223-235. <https://doi.org/10.1016/j.jclepro.2015.12.110>
- Sverdrup, H.U., and Olafsdottir, A.H. (2023). Dynamical modelling of the global cement production and supply system, assessing climate impacts of different future scenarios. *Water, Air, and Soil Pollution*, 234(3):191. <https://doi.org/10.1007/s11270-023-06183-1>
- Thankam, G.L., and Thurvas R. N. (2020). Ideal supplementary cementing material - Metakaolin: A review. *International Review of Applied Sciences and Engineering IRASE*, 11(1):58-65. <https://doi.org/10.1556/1848.2020.00008>
- Thomas, M., Hooton, R.D., Rogers, C., and Fournier, B. (2012). 50 years old and still going strong. *Concrete International*, 34:35.
- Wild, S., Khatib, J.M., and Jones, A. (1996). Relative strength, pozzolanic activity and cement hydration in superplasticised metakaolin concrete. *Cement and Concrete Research*, 26(10):1537-1544. [https://doi.org/10.1016/0008-8846\(96\)00148-2](https://doi.org/10.1016/0008-8846(96)00148-2)
- Yuan, Y., Niu, K., Tian, B., Li, L., Ji, J., and Feng, Y. (2023). Effect of metakaolin on the microstructural and chloride ion transport properties of concrete in ocean wave splashing zones. *Materials*, 16(1):7. <https://doi.org/10.3390/ma16010007>
- Zhang, S., Zhou, Y., Sun, J., and Han, F. (2021). Effect of ultrafine metakaolin on the properties of mortar and concrete. *Crystals*, 11(6):665. <https://doi.org/10.3390/cryst11060665>