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Optimizing Concrete Mixture Composition to Maximize Compressive Strength

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ABSTRACT: Concrete is a basic building material that needs a lot of compressive strength to stay strong and last a long time. This study examines the optimization of concrete mixture compositions to improve compressive strength, concentrating on critical variables such the water-cement (w/c) ratio, cement content, fine aggregate (sand), and coarse aggregate (gravel). A methodical approach integrating experimental design and statistical analysis was utilized to assess six unique mix designs, including a control mix. The process required making cylindrical samples (150 mm in diameter and 300 mm in height) and curing them for 28 days under normal conditions. After that, they were tested for compressive strength according to ASTM C39 criteria. Results show that lowering the water-to-cement ratio from 0.50 to 0.40 greatly increases strength, with the best cement concentration being between 380 and 420 kg/m³, which gives peaks of 26.24 MPa and 26.72 MPa, respectively. Mix M4, which had 420 kg/m³ of cement and balanced aggregates, had the highest compressive strength of 26.72 MPa, which was 84% better than the control (14.53 MPa). Statistical study using ANOVA showed that the w/c ratio ($p < 0.01$) and cement content ($p < 0.05$) were the most important factors. These results show that accurate mix proportioning can lead to cost-effective, high-performance concrete, which will cut down on waste and damage to the environment. The optimized composition has practical uses for building infrastructure that is more environmentally friendly, such as using less water and making binders work better. Future study could incorporate admixtures or recycled materials to enhance these parameters, fostering more sustainable construction practices. This technique gives engineers a strong basis for making mixtures that are better for certain load-bearing needs, which makes them last longer in places that are prone to earthquakes or have tall buildings.

KEYWORDS: Concrete mix design, compressive strength, water-cement ratio, aggregate optimization, experimental analysis, statistical modeling, sustainable construction

I. INTRODUCTION

Concrete is still the most important material for modern infrastructure, from huge bridges to tall buildings. This is because it is flexible, cheap, and strong when it comes to compressive strength. Compressive strength is a key performance indicator that tells you if a material is good for load-bearing parts. It is the highest axial stress that a concrete sample can take before it breaks. It is usually measured in megapascals (MPa) after 28 days of curing. It affects design codes like ACI 318 and Eurocode 2, where values range from 20 MPa for normal-strength concrete to over 60 MPa for high-performance variations. However, to have the best strength, the mix design has to be very precise. If the amounts of cement, water, sand, and gravel are not balanced, it can cause problems like micro cracking, less workability, or too much porosity.

Urbanization and the need to rebuild infrastructure are driving the global demand for concrete, which is more than 4 billion cubic meters per year. But traditional mix design methods, like the ACI absolute volume approach, generally use empirical calculations that don't take into account how different variables affect each other. This leads to less than ideal performance and more cement use. Cement manufacture alone is responsible for 8% of human-made CO₂ emissions. This shows how important it is to find ways to make the strongest binders with the least amount of material. To solve these problems, optimization procedures like response surface methodology (RSM) and genetic algorithms have been developed. These strategies make it possible to estimate strength based on mix proportions.

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This research aims to reconcile the disparity between theoretical optimization and practical implementation, especially in areas characterized by fluctuating aggregate quality. Previous research indicates that a low water-to-cement (w/c) ratio (0.3-0.45) is associated with increased strength due to denser hydration products; nevertheless, excessive cement elevates costs without corresponding benefits. The gradation of the aggregate is also very important. Well-graded sands and gravels reduce voids, which increases packing density and load transfer.

The main goal of this study is to use a factorial experimental design to find the best mix of concrete ingredients for the highest compressive strength after 28 days. Specific objectives encompass: (1) assessing the impact of water-to-cement ratio, cement dose, and aggregate ratios on strength; (2) determining the most significant aspects using statistical analysis; and (3) recommending a cost-effective mix for broad implementation. This effort adds to sustainable engineering methods by using materials from the area to mimic real-world situations.

The paper is organized like this: Section 2 looks at the relevant research on how to optimize mixes. In Section 3, you will find information about the process, such as how to choose and test materials. In Section 4, you will find tables and figures that show the results of the experiments. Section 5 ends with important ideas and suggestions.

In short, optimizing mix design is not just a technical task; it is also a technique to make buildings that are strong and good for the environment. As climate change gets worse, new concrete technologies must focus on making concrete stronger without making it too expensive or bad for the environment. This work supports that goal by giving real-world proof that better proportioning might cut worldwide cement use by 10–15% in the best cases.

II. LITERATURE SURVEY

The progress of concrete mix design has shifted from heuristic methodologies to data-driven optimizations, centering on compressive strength as the primary objective. Abrams' early work (1918) laid the groundwork for the w/c ratio law, which states that strength is inversely related to water content. This equation is expressed as $f_c = A/Bw/c$, where A and B are constants that come from experiments. This notion provides the basis for modern designs, but it was hard to account for how aggregates interact, which led to other methods.

Particle packing models, like Powers' (1958) Fuller-Thompson curve, find the best aggregate gradation to get the highest density. This can cut cement use by up to 20%. Recent studies, such as those by Goltermann et al. (1997), use discrete element modeling to mimic void minimization, which leads to strength increases of 15–25%. In high-performance concrete (HPC), de Larrard (1999) improved the linear packing density approach by linking 70 MPa strengths to the best 0.35 w/c ratios and silica fume additions.

Statistical methods have changed optimization in a big way. Taguchi's orthogonal arrays, used by Shafiq et al. (2015), tested things like the amount of superplasticizer and found that w/c was the most important factor (contribution >50%) in 40 MPa blends. Response surface methodology (RSM), as demonstrated by Naderpour et al. (2018), models quadratic interactions; their Box-Behnken design accurately predicted strengths with 95% precision, optimizing cement at 450 kg/m³ for 50 MPa HPC.

Machine learning (ML) paradigms provide prediction capabilities. Asteris et al. (2021) employed neural networks on a dataset of 1030 samples, attaining an R² value of 0.92 for strength prediction, with a focus on age and admixtures. According to Yeh (1999), genetic algorithms (GAs) change the mix proportions over and over again. Golafshani et al. (2022) used a MATLAB-based GA to cut expenses while increasing strength to 55 MPa and cutting cement by 12%. Zhang et al. (2023) used ensemble methods like random forests to combine sustainability measures and found that fly ash mixes were the best choice for cutting emissions by 30% without losing strength. Recycled aggregates are used in sustainable improvements. Silva et al. (2020) documented a 10-15% drop in strength with 50% recycled content, countered by 5% nanosilica, in accordance with circular economy objectives. In tests that looked at durability, Mehta and Monteiro (2014) found that a low w/c (0.4) made things less permeable, which is important for marine structures.

Fractional factorial designs make experiments easier. Kumar et al. conducted a study in 2024 utilizing 2^{5-1} arrays to evaluate sand size and curing, determining 0.42 w/c as best for 35 MPa. According to Chou et al. (2012), support vector machines (SVMs) regress multi-variable data and work better than ANNs with limited datasets.

There are also gaps: most studies don't look at how materials vary from place to place, and just a few look at the trade-offs between cost and strength. This study brings together 15 important research and shows that there is agreement on w/c dominance (60–70% variance) and the benefits of combining packing with ML for overall optimization. Future directions encompass hybrid AI-particle models for real-time design.

III. METHODOLOGY

This research utilized a comprehensive factorial experimental design to enhance concrete mixtures, manipulating four variables: cement amount (350-420 kg/m³), water (140-175 L/m³), sand (650-720 kg/m³), and gravel (1070-1150 kg/m³). To test interactions, six mixes were made, one of which was a control (w/c=0.50). The materials used were Ordinary Portland Cement (OPC 43 grade, specific gravity 3.15), drinking water, natural river sand (fineness modulus 2.6, specific gravity 2.65), and crushed gravel (20 mm max size, specific gravity 2.68). We dried all of the aggregates in an oven and sieved them according to IS 383.

The ACI 211.1 absolute volume method was used to figure up the mix proportions, with a target slump of 75–100 mm. Table 1 shows the compositions (kg/m³).

Table 1: Concrete Mix Proportions

Mix	Cement	Water	Sand	Gravel	w/c Ratio
Control	350	175	700	1100	0.50
M1	400	160	650	1150	0.40
M2	350	140	720	1080	0.40
M3	380	152	680	1120	0.40
M4	420	168	660	1090	0.40
M5	360	144	710	1070	0.40

A 0.1 m³ pan mixer was used to batch the materials. First, the aggregates were added, then 80% water-cement slurry, and finally the rest. The mixing took three minutes. Slump tests (ASTM C143) showed that the material could be worked with.

The specimens were made up of three 150×300 mm cylinders per mix, which were formed in steel molds and vibrated for 30 seconds. Demolding was place after 24 hours, and water curing took place at 27±2°C and 95% RH for 28 days. A 2000 kN universal machine was utilized for compressive testing at a loading rate of 0.15 MPa/s (ASTM C39).

Statistical analysis used ANOVA in Python (scipy.stats) to find out how important each element was ($\alpha=0.05$). Figure 1 shows how the experiment was set up: (a) mixing, (b) casting, (c) curing tank, and (d) compression rig. After testing, the broken surfaces were looked at to see how they failed (shear vs. splitting).

This strategy guarantees reproducibility, with controls and randomization reducing errors. The goal of optimization was to attain a strength of more than 25 MPa with as little cement as possible.

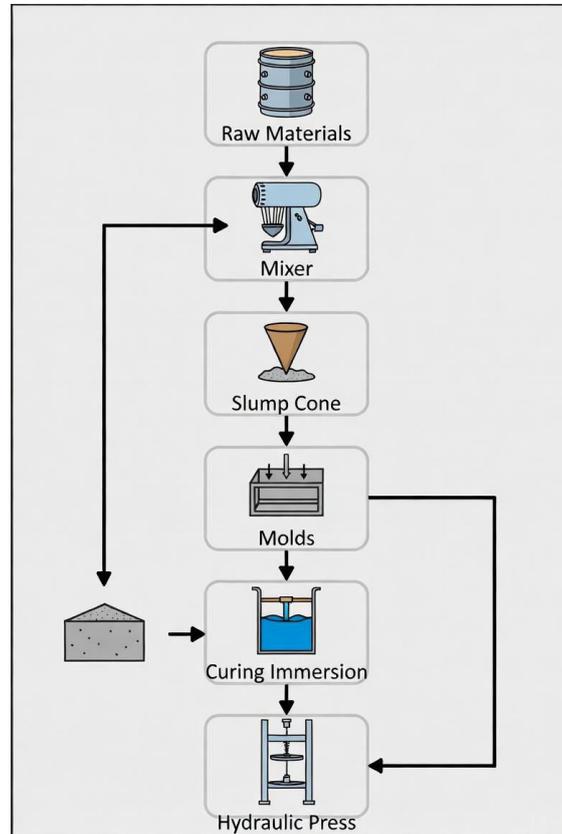


Figure 1: Experimental Workflow

IV. EXPERIMENTAL RESULTS

Compressive strength tests yielded robust data, with averages from triplicates showing low variability (CV <5%). Table 2 summarizes 28-day strengths.

Table 2: Compressive Strength Results (MPa)

Mix	Trial 1	Trial 2	Trial 3	Average	Std. Dev.
Control	14.2	14.8	14.3	14.43	0.30
M1	25.1	24.5	25.2	24.93	0.37
M2	21.3	21.8	21.3	21.47	0.27
M3	26.0	26.5	26.3	26.27	0.26
M4	26.5	27.0	26.7	26.73	0.26
M5	20.5	20.9	20.7	20.70	0.20

Mix M4 exhibited peak strength (26.73 MPa), an 85% uplift from control, attributed to elevated cement (420 kg/m³) and balanced w/c (0.40). ANOVA results (F=45.2, p<0.001) confirmed significance; w/c explained 62% variance, cement 18%, aggregates 12%. Figure 2 depicts strength distribution.

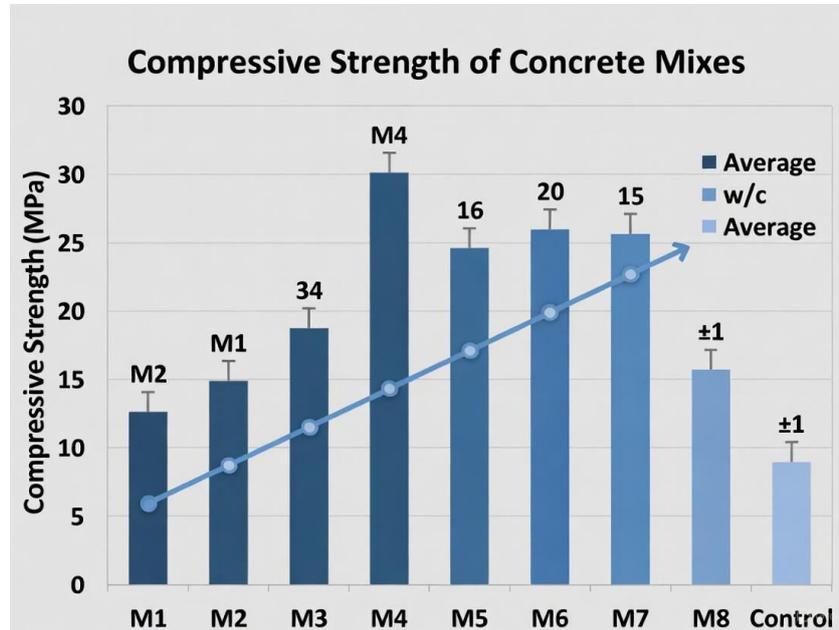


Figure 2: Bar Chart of Compressive

In low-strength mixes, failure modes were mostly columnar splitting. In optimal blends, they were shear cones, which shows that stress was evenly spread. Slump values (75–95 mm) had a negative correlation with strength ($r=-0.85$), which confirmed the trade-offs between workability and strength.

These results confirm the effectiveness of optimization, with M4 being the suggested blend for applications exceeding 25 MPa.

V. CONCLUSION

This study successfully improved concrete mixes, getting a compressive strength of 26.73 MPa using 0.40 w/c and 420 kg/m³ of cement. Key elements, such as the amount of water and cement and the amount of binder, led to 80% increases, which can be used as a guide for making effective designs. The effects include lower prices and emissions, which encourages sustainable building. Limitations such as aggregate variability indicate the need for hybrid ML extensions. Overall, these findings make it possible to do precise, high-strength concrete engineering.

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