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Economic and Structural Impacts of Engineered Mix Designs Over Volumetric Concrete Practice in Kathmandu Valley

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ABSTRACT

Nominal 1:2:3 volumetric proportioning is dominant in producing M20 concrete in the Kathmandu Valley, often without any proper quality control measures. The international codes limit the use of volumetric batching since it cannot ensure the required water-cement ratio. However, no research has been carried out regarding the impact of this system on the strength and cost of Kathmandu Valley's aggregates. To close this gap, a survey was carried out at 19 construction sites, showing 72.72% of M20 sites using a 1:2:3 proportion and only 27.27% conducting laboratory-based cube tests. A parallel laboratory test compared field-representative mixes against IS-code designed mixes across two test sets with two different aggregate combinations varying in their grading zones, fineness modulus, abrasion resistance and density. The field mixes failed the IS 456 average strength criteria for both systems (Test Groups 1 and 2) although individual cubes were above the characteristic 17 MPa level and mixes at water-cement ratio 0.55 failed acceptance regardless of aggregate source. Over a small range of NRs 13,240-13,950/m^3 , compressive strength varied between 17.9 and 36.4 MPa, indicating considerable scope for cost optimization even without an increase in material cost. The use of better-graded and harder aggregates resulted in higher-strength and lower-cost concrete as compared with poor-graded fine aggregates along with soft gravel. The above results indicate the requirement of mandatory testing of cubes, proper concrete mix design, and aggregates on a case-by-case basis as essential prerequisites for structurally reliable and cost-effective concrete production, especially in seismically prone Kathmandu Valley.

INTRODUCTION

Concrete remains supreme as the most extensively used construction material, with global production figures well over 10 billion per year (Khaffaf et al., 2024). Its structural performance is highly dependent upon the composition of its components, i.e. the proportions of cement, fine aggregates, coarse aggregates and water. Mix design is the systematic process of selecting these proportions to get targeted strength, workability and durability. Established standards and codes include IS 10262:2019 (Bureau of Indian Standards, 2019), ACI 211.1 (American Concrete, 1989), and the British DoE approach, which provide procedural guidelines, based on established scientific principles, for the rational selection of concrete mix proportions in field implementation. These frameworks relate aggregate characteristics, water-cement ratio, and the quantity of cement needed to achieve a desired mean strength, with appropriate allowance for variability. Studies have shown that the water-cement ratio and aggregate properties have the greatest impact on concrete compressive strength (Amin et al., 2022; Neville, 2011). Similarly, the interaction between aggregate and cement paste governs workability and mechanical properties of concrete, where interfacial transition zone integrity plays a critical role in overall strength development (Ahmed & Rahman, 2015). However, in many practical contexts, simplified volumetric mix proportions such as 1:2:4, which nominally corresponds to an M15 grade, are often used instead of a detailed mix design approach, irrespective of aggregate properties, moisture content, or required grade (Maruthachalam et al., 2021).

The Kathmandu Valley serves as a clear example of the consequences caused of the aforementioned gap. Located at the junction of the Indian and Eurasian tectonic plates in one of the world's most active geologic fault lines, Kathmandu Valley is one of the most seismically vulnerable urban landscapes in South Asia. This was made very clear by the 2015 Gorkha earthquake (Mw 7.8) that devastated a large portion of Nepal, which had been found to have suffered from poor concrete quality, oversized sections, and inadequate foundation systems, found through structural investigations conducted in the aftermath of the disaster (Adhikari & Gautam, 2018) (Gautam et al., 2016). The 2015 Gorkha earthquake alone has caused more than half a million buildings in Nepal to be either destroyed or irreparably damaged, thus making it a turning point for awareness regarding construction quality.

Several studies have revealed that volumetric batching leads to increased variability in concrete strength and ultimately, reduced performance compared to weight batching, affecting overall construction quality and efficiency (Maruthachalam et al., 2021; Yahya et al., 2025). (Prajapati & Karanjit, 2019) reports that variations in coarse aggregate sources alone can cause up to 47% deviation in target compressive strength. Even though 1:2:3 concrete is proportioned based on its nominal strength requirement, its actual strength falls short of the targeted characteristic strength, mostly due to the neglect of variables like moisture content of aggregates, specific gravities of aggregates, and gradations of fine aggregates. All these variables significantly influence the effective w/c ratio and volume of the cement paste in a mixture (Amin et al., 2022) (Shetty, 2019). In addition, poor grading of fine aggregates, specifically those belonging to Zone IV of the IS 383 standard (Bureau of Indian Standards, 2016), entails excessive fine materials with a larger surface area to wet, resulting in the need for extra water to maintain the same workability, ultimately lowering the strength of the concrete. Because nominal volumetric practices lack strict quality control frameworks, this extra water is routinely added on-site without a corresponding adjustment to the cement dosage, directly increasing the water-cement ratio and reducing the final compressive strength (Gautam et al., 2016; Monteiro & Mehta, 2006). Despite the factors affecting the quality of nominal mixes, current construction practices in the Kathmandu Valley often result in concrete without assurance of required strength (Prajapati & Karanjit, 2019).

Economic constraints and a lack of optimized design often lead small or medium-scale construction firms to rely on traditional nominal mixes measured via volumetric batching, rather than implementing a proportioned designed mix approach (Gautam et al., 2016; Yahya et al., 2025). Nonetheless, in case the nominal mixes do not yield the desired strength, the additional cost of increasing the size of members in order to compensate for low concrete strength is much higher than mix design (Chhachhia, 2021; Neville, 2011). There could be significant variations in strengths achieved through mix proportioning, even when the costs involved in material remain relatively unchanged, meaning that optimally designed mixes are not necessarily more costly than improperly proportioned nominal mixes. Various studies found that the optimal design of mixes through standard procedures like IS codes is cost-effective while reliably meeting strength criteria (Demissew & Aydın, 2022).

The existing literature pertaining to the quality of construction in the Kathmandu Valley mainly focuses on the damage assessment and performance evaluation of various structures after the earthquake. However, limited experimental analysis has been done so far in terms of linking prevalent concrete mix practices to quantifiable strength and cost outcomes. At the global level, international concrete standards explicitly restrict volumetric batching because it cannot maintain strict control over the water-cement ratio. Consequently, a distinct gap persists in the literature regarding how highly variable aggregate properties, such as distinct river lithologies, grading zones, and uncorrected surface moisture, interact within these fixed-volume mixtures to compromise structural safety margins and increase economic waste. This study addresses that gap by combining a structured questionnaire survey of construction sites in Kathmandu Metropolitan City and the adjacent valley with a controlled experimental investigation using two prevalent aggregate source combinations. The specific objectives of the paper are to: (i) document the prevalence and characteristics of nominal volumetric batching for M20 concrete in Kathmandu valley, (ii) compare 28 days compressive strength performance of a representative field mix against IS code designed mixes under controlled lab conditions, (iii) evaluate acceptance with reference to IS 456 criteria, (iv) perform statistical and economic analysis to quantify optimization potential available without substantial additional expenditure, and (v) assess the role of aggregate source and grading in facilitating the cost strength relationship for locally available materials.

MATERIALS AND METHODS

Study Design Overview

The study is divided into a two-step sequential approach. In the first phase, a survey was carried out by means of a structured field questionnaire on concrete mix practices at different construction sites located within Kathmandu Metropolitan City and surrounding valley municipalities. The second phase involved an experiment conducted in the laboratory for comparison between field and designed mixes based on the most common aggregate source combinations selected from the first phase survey findings for M20 concrete. Cost analysis was part of the experimental program, and statistical measures such as standard deviation, coefficient of variation, and Pearson correlation were derived from the experimental data obtained. The overall research workflow from survey design through to analysis and conclusions is depicted in Figure 1.

Governing Standards

Mix proportioning for designed groups adhered to IS 10262:2019 standards (Bureau of Indian Standards, 2019). Aggregates grading zones were defined in accordance with IS 383:2016 standards (Bureau of Indian Standards, 2016). For compressive strength evaluation, IS 456:2000 acceptance criteria for M20 (fck = 20 MPa) were applied: (a) Individual acceptance criterion: each cube must achieve a compressive strength ≥ fck − 3 = 17 MPa; and (b) Mean strength criterion: the average of any three consecutive test results must be ≥ fck + 4 = 24 MPa (Bureau of Indian Standards, 2000). The mean criterion is derived from statistical reliability requirements and is based on the assumed standard deviation. IS 456 specifies a minimum assumed standard deviation of 4.0 MPa for M20, yielding a required mean strength of 24 MPa.

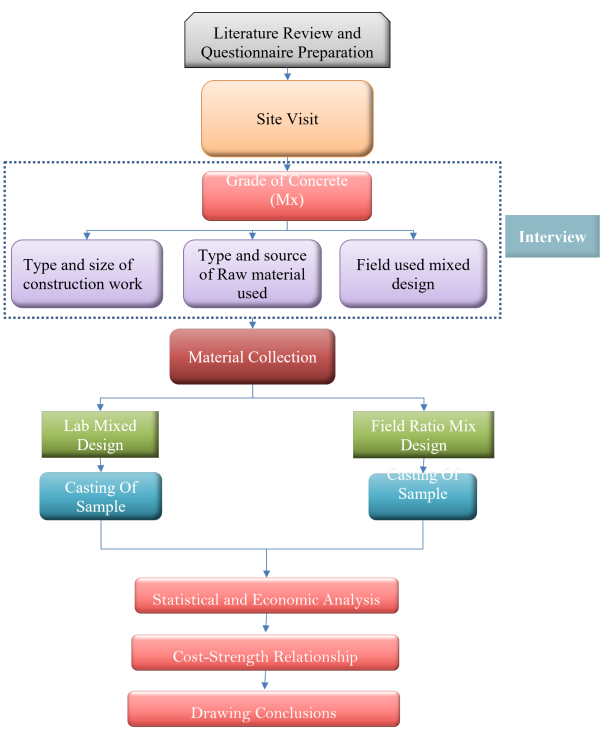

Figure 1. Research Methodology Flowchart

Phase I: Questionnaire Survey The surveys were conducted in 19 active construction sites located within Kathmandu Metropolitan City (16 sites) and the adjacent valley (Lalitpur and Tarkeshwor) (3 sites). Sites were selected through a convenience sampling approach targeting active construction sites in accessible locations across different wards and building use categories. While this approach limits statistical generalizability, it was considered appropriate for the exploratory and descriptive objectives of the survey phase. It is recommended that future studies adopt a stratified random sampling framework for more representative inference. A standard set of questions was prepared after an extensive literature review to learn about perspectives on the application of mix design in construction. Interviews were conducted with the contractors and workers to obtain their insights on mix design practices. The data collected include the purpose and scale of the building, grades of design concrete and cement, source of fine aggregate and coarse aggregate, nominal mixing ratios, and whether there had been any laboratory-based cube test done for compressive strength.

Phase II: Experimental Programme

Ordinary Portland Cement (OPC) Grade 43, adhering to IS 8112:2013 (Bureau of Indian Standards, 2013), was used in all concrete mixes, being the most dominant grade according to the survey. They were taken from a single batch of the same manufacturer throughout all experimental mixes to eliminate inter-batch variability. To verify material consistency and structural compliance before experimental batching, the physical and chemical properties of the cement were certified against the requirements of NS 572:2076 (Nepalese Standard for OPC-43). Standard laboratory testing procedures covered fineness, setting times, soundness via Le-Chatelier and autoclave expansion, and standard mortar cube compressive strengths at 3, 7, and 28 days. The certified physical parameters of the cement batch are summarized in Table 1.

Table 1: Physical Properties of OPC 43-Grade Cement

Physical Parameters	Test Result	NS 572:2076 Requirement
Normal Consistency (%)	27.6	–
Fineness (m^2/kg)	321	$>$ 225
Initial Setting Time (min)	220	$>$ 45
Final Setting Time (min)	275	$<$ 600
Le-Chatelier Expansion (mm)	0.5	$<$ 10
Autoclave Expansion (%)	0.15	$<$ 0.80
3-Day Compressive Strength (MPa)	34.7	$>$ 23
7-Day Compressive Strength (MPa)	43.0	$>$ 33
28-Day Compressive Strength (MPa)	56	$>$ 43

The experimental framework was organized into two independent, parallel tests, referred to as Test Set 1 and Test Set 2, which were selected based on their prevalence in the survey. Test Set 1 consisted of Trishuli riverbank black sand (fine aggregate, FA) and Melamchi white coarse aggregate (CA). Test Set 2 consisted of Dhading Baireni double-wash yellowish-white sand (FA) and Dhading Mahadevbesi black coarse aggregate (CA). Properties of the aggregates such as specific gravity, bulk density, water absorption capacity and sieve analysis were determined using IS 2386 procedure (Bureau of Indian Standards, 1963) and the grading zone of the fine aggregate was classified using IS 383:2016 (Bureau of Indian Standards, 2016). Aggregate Impact value (AIV) and Los Angeles Abrasion Value (LAAV) of the coarse aggregate sources were also determined due to their influence on concrete strength and durability against loads (Monteiro & Mehta, 2006). The consolidated physical and mechanical properties of all aggregates are presented in Table 2, while their particle size distribution curves are presented in Figure 2 for fine aggregates and Figure 3 for coarse aggregates, allowing a direct visual comparison of gradation across sources.

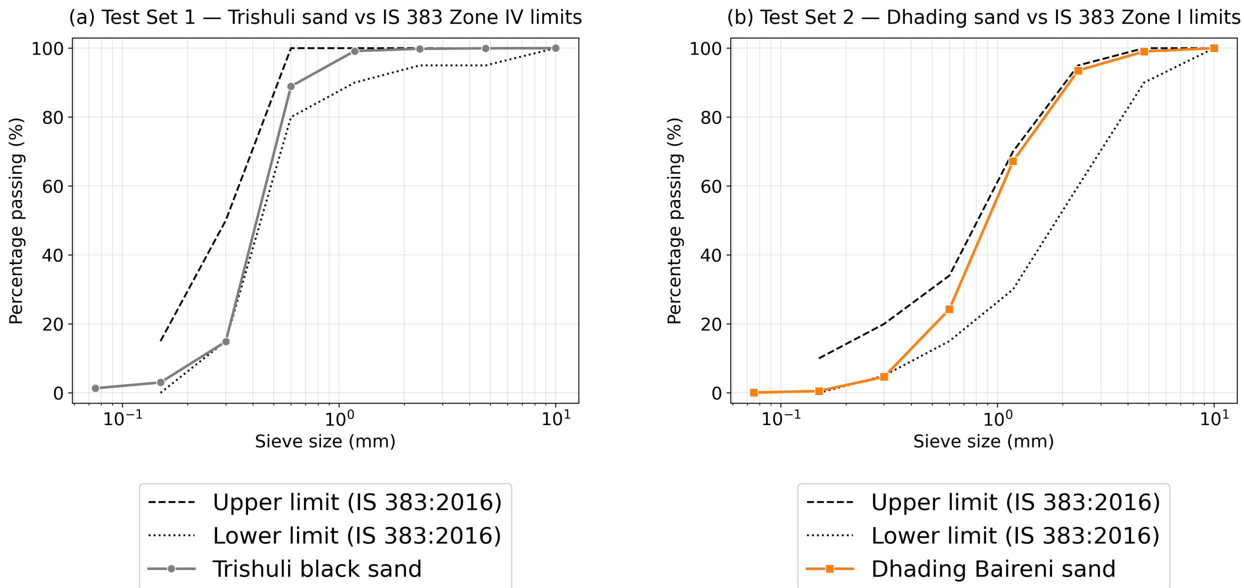

Figure 2. Particle size distribution of fine aggregates for (a) Test Set-1 (b) Test Set-2

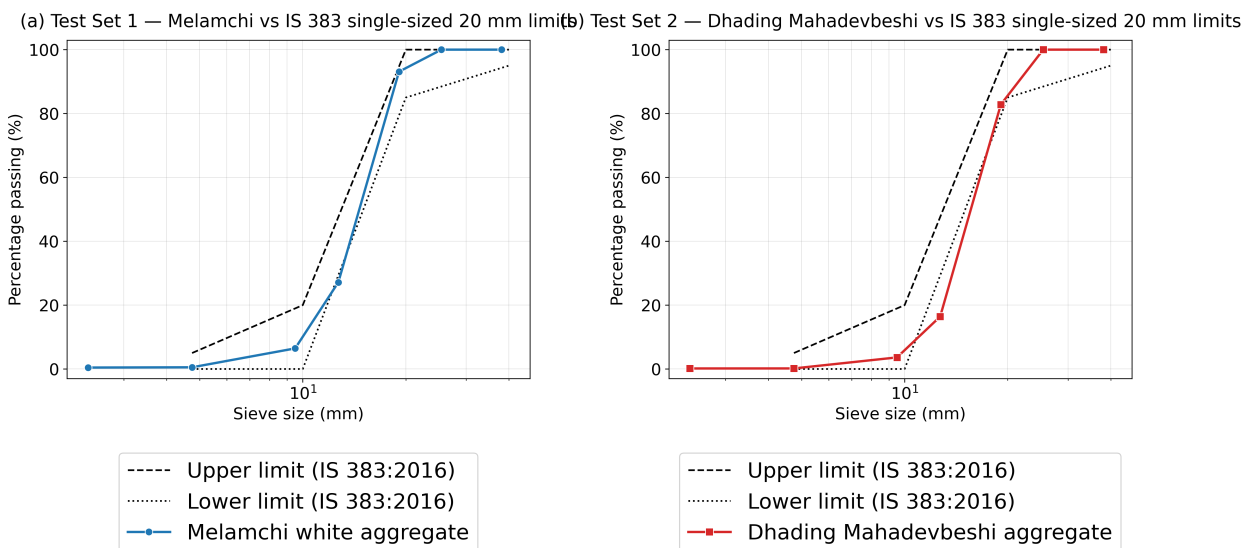

Figure 3. Particle size distribution of Coarse aggregate for (a) Test Set 1 (b) Test set 2

For both independent test sets, five different mixing groups were created. Out of these five groups, four were made by using the IS Code design mix concept for achieving M20 grade concrete using Grade 43 OPC as per the IS 10262 recommendations with varying water-cement (w/c) ratios. To facilitate cross-set performance comparisons, alphabetical pairs were assigned to parallel mix groups across the two sets that shared similar target parameters. Group A (Set 1) and D (Set 2) represent the mix with a w/c ratio of 0.50 with standard water content, while Groups B (Set 1) and E (Set 2) represent an elevated w/c of 0.55 obtained by keeping water content the same. Similarly, Group C (Set 1) and F (Set 2) represent a reduced w/c of 0.45 obtained by increasing cement content, and Groups I (Set 1) and J (Set 2) represent a w/c of 0.50 but with lower water content. For every test set, a practical field mixture was used as Group G (Test set one) and Group H (Test set two), batched at the nominal 1:2:3 vol-

Table 2: Physical and Mechanical Properties of Aggregates Used in the Experimental Program

Source	Type	Set	IS 383 Zone	Sp. Gravity	Bulk Density (kg/m^3)	FM	AIV (%)	LA Value (%)	Water Absorption (%)	Moisture Content (%)
Trishuli riverbank black sand	Fine	1	Zone IV	2.45	1,296	1.94	–	–	3.83	3.68
Dhading Baireni double wash yellowish white sand	Fine	2	Zone I	2.42	1,310	3.11	–	–	5.15	2.74
Melamchi white	Coarse	1	–	2.63	1,550	6.99	22.98	36.65	0.92	0.62
Dhading Mahadevbesi black	Coarse	2	–	2.70	1,565	7.13	22.58	33.21	0.94	0.93

Note: FM = Fineness Modulus; AIV = Aggregate Impact Value; LA = Los Angeles Abrasion Value; – = Not Applicable.

umetric ratio (Cement: Sand: Coarse aggregate) without any moisture correction to replicate the as-batched condition on Kathmandu valley construction sites.

The physical and mechanical properties of the aggregates were evaluated in accordance with IS 2386 (Part III). The test results show the permanent water absorption capacities to be 0.92% for Melamchi White Coarse Aggregate, 0.94% for Dhading Black Coarse Aggregate, 5.15% for Dhading (Yellow) sand, and 3.83% for Trishuli Black Sand. Additionally, the free surface moisture content of the aggregates remaining above the Saturated Surface Dry (SSD) condition were measured at 0.62%, 0.93%, 2.74%, and 3.68% for respective materials on the day of mixing. Moisture corrections based on these measured absorption and surface moisture values of each aggregate were applied to all four designed groups prior to batching. Conversely, as noted, these moisture values were intentionally left unadjusted in the nominal field mixtures (Groups G and H) to preserve the uncorrected, high-effective-water batching conditions prevalent in local practice.

Mix proportions for the designed groups were selected according to IS 10262. For M20 Grade concrete, the target mean strength is calculated as, $f_t = f_{ck} + 1.65 \times S$, where $f_{ck} = 20 \wedge S = 4$, giving a target mean strength of 26.6 MPa. Adopted w/c ratios were 0.45, 0.5, and 0.55 for the different designed groups.

In the case of the reference design group, the water content for a 20 mm maximum aggregate size is taken as 186 kg/m^3 and increased to 197.16 kg/m^3 to reach the target slump value of about 100 mm. The quantity of cement is calculated from the adopted w/c ratio and compared with the minimum cement content value. Ratio of fine aggregates to total aggregates is taken as 40%, and the coarse aggregate to total aggregate ratio is 60%. The absolute volume method was then used to calculate the quantities of fine and coarse aggregates based on their measured specific gravities. Moisture corrections were applied to designed mixes using the measured absorption and surface moisture contents of each aggregate source, while the nominal field mixes were batched without moisture correction to represent common site practice. The summary table showing the material proportions for each group is presented in Table 3.

For both experimental groups, three cubes of dimension 150 mm × 150 mm × 150 mm were molded using steel molds to produce a total of thirty specimens, with the experimental setup as shown in Error: Reference source not found. These were rodded in three equal layers as per IS 516 specifications (Bureau of Indian Standards, 2018) and allowed to cure under ambient conditions of temperature of approximately 18–24°C in a water curing tank for 28 days following removal from the molds after 24 hours. The compressive strength of each cube was evaluated from the maximum force recorded at failure divided by the nominal cross-sectional area of 22,500 mm^2, while the average compressive strength of the cubes for each experimental group was obtained from the data from three cubes of each group.

Material cost per cubic meter of concrete was determined for each group on the basis of the same unit rate market costs applied to the amount of materials used in each unit volume: cement costing NRs 12 per kg, both fine and coarse aggregates NRs 4.29 per kg, and water NRs 1 per kg. These rates reflect prevailing Kathmandu market conditions at the time of the study and are applied uniformly across all groups so that cost differences are attributable entirely to proportioning rather than to price variation. The strength-per-unit-cost index, which is defined as the ratio of mean compressive strength per cubic meter in megapascals (MPa) to 1,000 NRs of material cost per cubic meter, was calculated for each group to enable relative ranking. It should be noted that the cost analysis presented herein considers direct material costs only and does not include additional implementation costs associated with technical manpower, equipment, routine lab tests and other overheads. Consequently, a comprehensive field-scale life cycle cost analysis is required to determine the net economic feasibility.

Within-group consistency was measured using the standard deviation (SD) and coefficient of variation (CoV) of the compressive strengths of the three concrete cubes. However, use of n = 3 specimens per group is the minimum specified by IS standards and represents a limitation for robust statistical inference. The coefficient of variation values reported should be interpreted with caution,

Table 3: Concrete mix proportions adopted for all mix designs

Test Set	Group	w/c	Cement (kg/m3)	Water (kg/m3)	Fine Aggregate (kg/m3)	Coarse aggregate (kg/m3)	Mix Ratio (C: FA: CA)
1 (Trishuli FA /Melamchi CA)	A	0.50	394.32	197.16	664.11	1069.35	1:1.68:2.71
	B	0.55	358.47	197.16	692.14	1069.18	1:1.93:2.98
	C	0.45	438.13	197.16	634.21	1064.85	1:1.45:2.43
	I	0.50	372.00	186.00	681.99	1098.14	1:1.83:2.95
	G	0.50	372.00	186.00	669.60	1201.25	1:1.80:3.23
2 (Dhading Baireni FA/ Dhading Mahadevbesi CA)	D	0.50	394.32	197.16	733.23	1069.35	1:1.86:2.71
	E	0.55	394.32	197.16	733.23	1069.35	1:2.13:2.98
	F	0.45	438.13	197.16	700.22	1064.58	1:1.60:2.43
	J	0.50	372.00	186.00	752.97	1098.14	1:2.02:2.95
	H	0.50	372.00	186.00	676.83	1212.88	1:1.82:3.26

due to high uncertainty at this sample size. Future studies are recommended to use n = 6 or n = 9 cubes per group to improve statistical reliability. For the analysis of test sets, the Pearson correlation coefficient between cost and the mean compressive strength was computed across the five groups in each set to assess the relationship between cost and strength.

Figure 4. Experimental Setup

RESULTS AND DISCUSSION

Survey Findings: Concrete Mix Practice in Kathmandu Valley

A total of 19 sites were covered under the field survey in relation to construction sites in residential (n = 13), commercial (n = 3), and institutional (n = 3) categories, with building heights varying from two to nine stores (refer to Table 4). Figure 5 (a) shows that M20 is the dominant concrete grade for residential buildings, while commercial and institutional projects show a slight shift toward M25 and M30. It was observed that there are some common practices associated with concrete production in the locality. First, M20 is by far the most frequently used concrete grade in 11 out of 19 sites (57.89%). The other grades (M25 and M30) are employed for large or tall commercial buildings. Secondly, the ratio of 1:2:3 is used by volumetric batching for M20 concrete in 72.72% (8 out of 11) cases. This method of mixing is further complicated by the lack of any verification process, as only 27.27% of M20 sites conduct the cube tests as illustrated in Figure 5 (b). Thirdly, water-cement ratio specifications were not adopted, as in all cases, water content was estimated by mere judgment based on concrete workability. However, material selection is highly standardized, with 43 OPC being commonly used and 53 OPC being used in M30 projects.

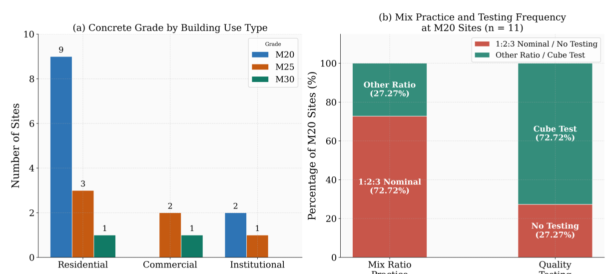

Figure 5. Survey Summary (a). Concrete Grade by Building Use Type (b). Mix Practice and Testing frequency at M20 Sites

The results of these studies, representing the sample structural concrete mixes used within the Kathmandu valley region, highlight the lack of quality control in terms of concrete grade composition. Uncontrolled water-cement ratio in the context of the 2015 earthquake aftermath is particularly concerning, given the sensitivity of seismic performance of reinforced concrete structures to concrete compressive strength. The lack of a standardized testing process for the M20 strength grade concrete does not allow for the identification of any deviation from the specifications. Thus, the structure faces an accumulative risk since the true structural integrity of the construction cannot be established.

Table 4: Summary of questionnaire survey data from Kathmandu Valley construction sites

S.N.	Site Code	Type	Storeys	Grade	Cement	Fine Agg. Source	Coarse Agg. Source	Mix Ratio (C: FA: CA)	Testing
1	KV-1	Residential	2	M20	43 Gr	Trishuli	Melamchi	1:2:3	None
2	KV-2	Residential	3	M20	43 Gr	Trishuli	Melamchi	1:2:3	None
3	KV-3	Residential	2.5	M20	43 Gr	Trishuli	Melamchi	1:2:3	None
4	KV-4	Residential	7	M30	43 Gr	Trishuli	Mahadevbesi/Melamchi	1:1.34:2	Cube
5	KV-5	Institutional	4.5	M20	43 Gr	Trishuli	Melamchi	1:2:3	Cube
6	KV-6	Residential	4	M20	43 Gr	Melamchi	Melamchi	1:1.5:3	None
7	KV-7	Residential	3.5	M20	43 Gr	Bhakunde/Kavre	Tikabhairav	1:2:3	None
8	KV-8	Residential	6	M25	43 Gr	Melamchi	Melamchi	1:1:2	Cube
9	KV-9	Residential	4.5	M25	43 Gr	Trishuli	Melamchi	1:1.75:2.5	Cube
10	KV-10	Commercial	7	M30	53 Gr	Dhading	Dhading Mhd.	1:1.5:3 / 1:1:2	Cube
11	KV-11	Residential	7	M25	43 Gr	Dhading	Dhading Mhd.	1:1.75:2.5	None
12	KV-12	Commercial	9	M25	43 Gr	Dhading Simle	Dhading/Belkhu	1:1.4:2.8	Cube
13	KV-13	Institutional	5	M20	43 Gr	Mahadevbesi	Mahadevbesi	1:1.5:3	Cube
14	KV-14	Institutional	3	M25	43 Gr	Dolalghat/Kavre	Dolalghat/Kavre	1:1:2	Cube
15	KV-15	Residential	2.5	M20	43 Gr	Tikabhairav	Tikabhairav	1:1.5:3	Cube
16	KV-16	Commercial	8	M25	53 Gr	Trishuli	Melamchi	1:2:3	None
17	KV-17	Residential	4	M20	43 Gr	Trishuli	Melamchi	1:2:3	None
18	KV-18	Residential	3.5	M20	43 Gr	Trishuli	Melamchi	1:2:3	None
19	KV-19	Residential	3	M20	43 Gr	Trishuli	Melamchi	1:2:3	None

Compressive Strength and Acceptance Evaluation

The data regarding the overall 28-day compressive strength measurements, variance measurements, material cost calculations, and the ratio of strength-to-cost for all ten groups of mixes have been tabulated in Table 5, along with their respective acceptability status according to the IS 456 specifications (Bureau of Indian Standards, 2000). In addition to that, the mean strength values for all mix groups have also been illustrated in Figure 6.

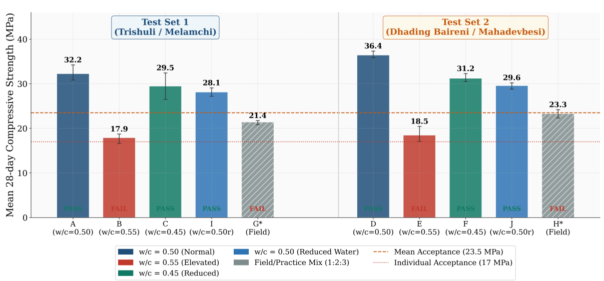

Figure 6. 28 days Compressive strength test result for (a) Test Set 1 (b) Test set 2

A clear pattern emerges from Table 5. The mixes involving field and practice (Groups G and H) have not met the requirement of 24 MPa of mean strength needed in order to be accepted according to the IS 456 mean strength test criterion, though individual cube strength has met the criterion by surpassing the 17 MPa minimum. The mean strength criterion is designed to verify the overall quality of the production process of concrete, while the individual criterion serves as a safety net to identify extreme outliers or localized failure (Farzan, 2018). Failure on the mean criteria under controlled lab conditions with aggregate moisture adjustment, minimal error on measurement variability, and human factor compared to site conditions, shows that the same mix produced on site would fail with considerably high probability.

Since the addition of water on site is usual to achieve proper workability, the effective in-situ w/c would be higher compared to the laboratory value, resulting in strength values falling even further from acceptable levels. According to (Monteiro & Mehta, 2006) water addition without control is one of the most common causes of understrength of concrete in tropical/subtropical construction sites. This effect has been quantified directly in recent production-scale testing: raising unit water content by only 25 kg/m^3 above the design value significantly increased porosity and reduced strength in ready-mixed concrete (Park et al., 2024). Because volumetric batching fixes proportions by gauge-box volume rather than by measured mass, this same uncorrected-water error compounds batch to batch rather than being adjusted out, consistent with the 10.8–13.1 MPa gap observed here between the unadjusted field mixes (Groups G, H) and their moisture-corrected counterparts (Groups A, D). The failure of the mean acceptance for the mixes with w/c = 0.55 (Group B & Group E) directly illustrates Abrams' Law (Yeh, 2006), which establishes that the compressive strength of concrete is inversely proportional to its water-to-cement ratio. At an elevated w/c ratio of 0.55, the high volume of free water increases paste porosity, fundamentally limiting the baseline strength potential of the matrix. While the mean compressive strengths of those groups (17.9 MPa for Set 1 and 18.5 MPa for Set 2) exceed the characteristic strength of M20 for individual criteria (individual acceptance 17 MPa) by a small margin, the value is far from the required average level. In practical terms, a w/c of 0.55 is not considered extreme in Kathmandu construction sites, especially since adding water to achieve a workable mix is standard practice during warm weather.

This means that considerable amounts of nominally designed M20 concrete could have been under-strength due to the addition of extra water, a risk that is invisible due to the absence of cube tests.

To mathematically validate whether the observed differences in compressive strength across the concrete were statistically meaningful rather than random lab variance, independent two-sample t-tests were conducted. The evaluation of engineering control against nominal practice shows that the engineered baselines significantly outperformed their volumetric field counterparts in both Test Set 1 (Group A vs. Group G: $t(4) = 10.23$, $p = 0.0005$) and Test Set 2 (Group D vs. Group H: $t(4) = 18.38$, $p = 0.0001$). Similarly, the evaluation of w/c ratio sensitivity, transitioning from an elevated 0.55 w/c to a reduced 0.45 w/c, yielded sharp, statistically significant strength gains in both Set 1 (Group B vs. Group C: $t(4) = -6.30$, $p = 0.0032$) and Set 2 (Group E vs. Group F: $t(4) = -11.12$, $p = 0.0004$). Despite the small sample size mandated by code-compliance testing ($n = 3$), these distinct p-values indicate the mechanical advantages of engineered concrete designs over local nominal practice.

Effect sizes are considerably large since the difference between field mixes and the best-designed mixes is large. In this respect, Group A outperformed Group G with 10.8 MPa more strength at a higher price of NRs 328 per cubic meter. On the other hand, Group D outperformed Group H by 13.1 MPa at a price of NRs 237 per m^3 only. Our results align with (Amin et al., 2022) showing proportioning control as the key parameter for improving strength.

Within Group Variability

Coefficient of Variation (CoV) serves as an effective indicator of mix consistency. The value of CoV for the designed mixes ranged from 2.2% for Group D to 10.1% for Group C, most of which did not exceed 6%. Meanwhile, the CoVs for the field or practice mixes appeared relatively low at 2.5% for Group G and 4.0% for Group H. While this result may appear reassuring, it only demonstrates that all the cubes in that particular batch are consistent among themselves. However, it does not guarantee that the mean is sufficient. In this case, consistency is merely consistency in poor strength. This illustrates the importance of reporting both consistency and mean strength together, as a mix can reliably be poor. While it is noted that a standard sample size of three cubes ($n = 3$) naturally limits broad inferential robustness, the variations still provide clear comparative insights. Group C exhibits high CoV at 10.1%, reflecting larger variations of individual cube strengths (26.5–32.4 MPa) at w/c = 0.45. While a sample size of three cubes ($n = 3$) is too small to definitively isolate the source of this variance, this elevated CoV highlights the inherent difficulty of maintaining tight within-batch consistency when handling stiffer, low w/c mixtures under standard laboratory conditions.

Cost-Strength Analysis and Optimization Potential

A significant finding of this study is the huge discrepancy in strength within the limited material-cost spread. According to Table 5, total material costs varied from NRs 13,240 (Group E) to NRs 13,949 (Group C), covering a gap of NRs 709, or about 5.35% of the lowest cost, with strengths varying from 17.9 MPa (Group B) to 36.4 MPa (Group D), nearly double the latter. This shows the potential of optimization as a small increase in material cost (less than 6%) brings a big difference in strength (more than 100%). Additionally, Figure 7 shows that reducing the w/c ratio increases the cost, but results in a significant strength gain, and field mixes provide the lowest strength, falling below the acceptance line, though being the cheapest.

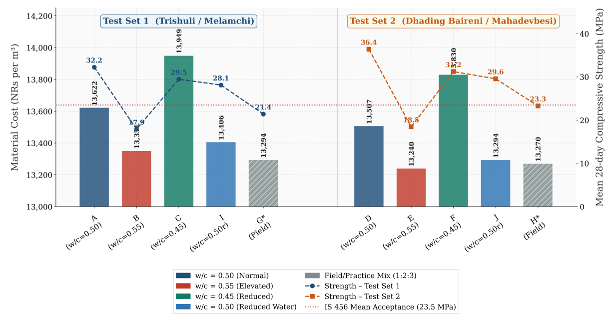

Figure 7. Material Cost (NRs per m3) and 28 days Compressive strength test result for (a) Test Set 1 (b) Test set 2

Pearson correlations for material cost and mean strength within the Set 1 group were $r = 0.67$ ($p = 0.21$) and $r = 0.62$ ($p = 0.27$) for the Set 2 group. With five data points per test set, these correlations have limited statistical power, with $p > 0.05$ in both showing non-significance at $\alpha = 0.05$ level. It shows that the observed upward trends lack sufficient statistical power to confirm a generalized population correlation. So, these relationships should be interpreted strictly as localized experimental design trends. Despite the general trends, the highest values of strength are not necessarily those having the highest cost. For example, in Test Set 2, Group D (w/c = 0.50, cost NRs 13,507) achieves the highest mean strength of 36.4 MPa and the highest strength-to-cost index of 2.70 MPa per 1,000 NRs, outperforming even Group F (w/c = 0.45, cost NRs 13,830) at 31.2 MPa. This shows that the optimal mix is not simply the one with the most cement, but one that most efficiently translates material into strength, given the specific aggregate combination in use.

The index values from Table 5 can be used as a basis to make an informed decision regarding which group will be most beneficial to use. Group D (Test Set 2, w/c = 0.50) has the largest index value at 2.70 MPa/1,000 NRs,

Table 5: 28-day compressive strength results, statistical metrics, cost, and acceptance evaluation

Test Set	Group	w/c	Mix Ratio (C: FA: CA)	Cube 1 (MPa)	Cube 2 (MPa)	Cube 3 (MPa)	Mean (MPa)	SD (MPa)	CoV (%)	Cost (NRs/m³)	Strength/Cost in 1000 Rs.	Result	Remarks
1 (Trishuli FA /Melamchi CA)	A	0.50	1:1.68:2.71	34.22	30.84	31.69	32.25	1.76	5.45	13,622	2.37	ACCEPT	Baseline
	B	0.55	1:1.93:2.98	18.71	16.62	18.36	17.90	1.12	6.25	13,351	1.34	REJECT	High w/c
	C	0.45	1:1.45:2.43	26.49	29.47	32.44	29.47	2.98	10.10	13,949	2.11	ACCEPT	Low w/c
	I	0.50	1:1.83:2.95	28.09	29.07	27.20	28.12	0.94	3.33	13,406	2.10	ACCEPT	Low water
	G	0.50	1:1.80:3.23	21.69	21.73	20.80	21.41	0.53	2.46	13,294	1.61	REJECT	Field mix
2 (Dhading Baireni FA/ Dhading Mahadevbesi CA)	D	0.50	1:1.86:2.71	35.82	36.09	37.33	36.41	0.81	2.21	13,507	2.70	ACCEPT	Baseline
	E	0.55	1:2.13:2.98	17.07	20.44	17.87	18.46	1.76	9.54	13,240	1.39	REJECT	High w/c
	F	0.45	1:1.60:2.43	32.27	30.93	30.49	31.23	0.93	2.97	13,830	2.26	ACCEPT	Low w/c
	J	0.50	1:2.02:2.95	30.22	28.80	29.69	29.57	0.72	2.43	13,294	2.22	ACCEPT	Low water
	H	0.50	1:1.82:3.26	23.38	22.31	24.18	23.29	0.94	4.03	13,270	1.76	REJECT	Field mix

with the next one being Group A (Test Set 1, w/c = 0.50) having a value of 2.37 MPa/1,000 NRs. Both field/practice groups have the smallest index values, that is, 1.61 and 1.76, respectively. It indicates that the mixture practiced is not only weaker but is the least cost-effective of them all in terms of structural efficiency for every amount of money spent. The cost-strength relationship across all groups shows "optimization peak" representing that increase in cost doesn't always mean an increase in strength (Figure 8).

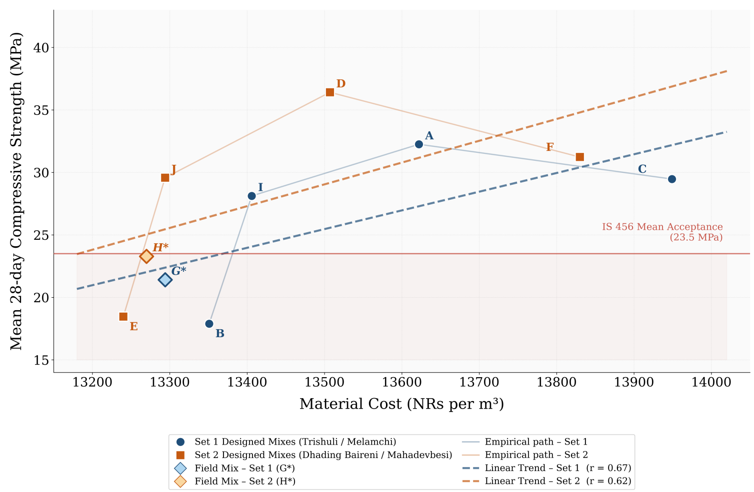

Figure 8. Scatter Plot of mean compressive strength (MPa) Vs. Material Cost (NRs/m3)

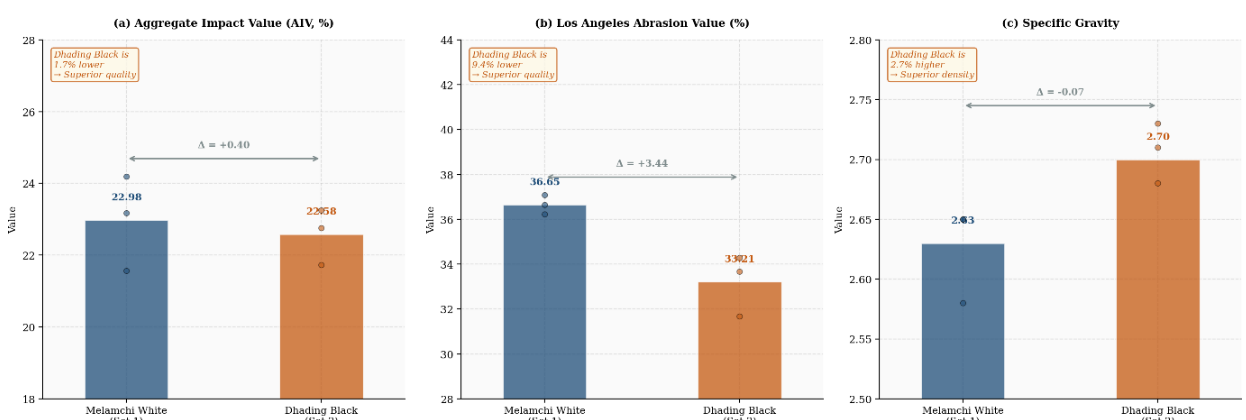

Figure 9. Bar chart comparing properties of two coarse aggregate sources showing (a) AIV, (b) LAAV, (c) Specific Gravity

Role of Aggregate Source and Grading

Test Set 2 (Dhading Aggregates) had an overall superior performance to Test Set 1 (Trishuli/Melamchi) in both strength and economy with respect to all water-cement ratios tested. The difference in results can be explained by the differences in the physical properties of the aggregate materials, which directly affect concrete performance. The comparison of major properties of coarse aggregate materials is shown in Figure 9 below.

Regarding fine aggregates, sieve analysis has shown that Trishuli black sand has a Fineness Modulus of 1.94 and falls into Zone IV of IS 383:2016 (Bureau of Indian Standards, 2016). The low modulus value was strictly verified through repeated lab grading tests to ensure data accuracy. On the other hand, Dhading Baireni sand has a Fineness Modulus of 3.11 and belongs to Zone I, indicating a coarser, better-graded particle distribution. Both fine aggregate specific gravities (2.45 & 2.42) are lower than the approximate range of 2.60–2.70 common for quartz-rich sand. Geotechnical and concrete property studies in Nepal have shown that local river sands of Trishuli deposits possess lower specific gravities attributed to presence of light density minerals (Mishra & Acharya, 2019). According to IS 383, the use of Zone IV sand should be exercised with extreme caution, only with designed mixes and close quality control. The use of superfine sands that fall outside standard construction specifications requires careful management because their high specific surface area absorbs more free water, reducing workability (Hattani et al., 2024). Especially during volumetric batching, additional water is often added arbitrarily to restore consistency, which increases the water-to-cement ratio and leads to higher porosity and a significant reduction in compressive strength. Therefore, Trishuli black sand was intentionally included in this comparative study to scientifically quantify the exact performance penalties that occur when such fine aggregates are used in local unengineered nominal mixes without standard blending practices.

For coarse aggregates, sieve analysis performed by two sources shows similar distributions, with most passing through the 19.1 mm sieve but remaining on the 9.5 mm sieve, consistent with nominal 20 mm aggregate. Mechanical tests show marked differences between the two aggregate types, wherein the black aggregate from Dhading Mahadevbesi has an LA abrasion value of 33.2% and an impact value of 22.6%, whereas the Melamchi white aggregate has 36.7% and 23.0% in the same order. LA and impact values less than 30% signify harder and more durable aggregate, capable of resisting crushing and abrasion effects, and should be used for aggregate in concrete for wearing surfaces (Bureau of Indian Standards, 2016). The specific gravity of Dhading Mahadevbesi aggregate (2.70) also exceeds that of Melamchi aggregate (2.63), yielding denser concrete with a more compact microstructure.

The overall aggregate quality difference accounts for the reason why Test Set 2 obtains a compressive strength of 36.4 MPa (Group D) versus 32.3 MPa (Group A) with the same w/c ratio and nearly equal cost. An independent t-test shows their difference as statistically significant ($t(4) = -3.73$, $p = 0.0203$). Moreover, Test Set 2 with a field mix of 23.3 MPa is superior to Test Set 1 with a field mix of 21.4 MPa, even though they both use the same 1:2:3 mix proportion, further highlighting the baseline material advantage of the Dhading aggregate ($t(4) = 3.03$, $p = 0.0387$). The pattern is consistent with recent comparative studies demonstrating that fineness modulus and grading zone are more important factors affecting strength when a constant w/c ratio is maintained due to the increased paste requirement in fine sand and hence reduced paste for bonding with the larger particles (Alabi, 2023).

These findings have a direct practical implication, showing that aggregate quality is also crucial for determining the possible concrete quality and cannot be ignored, especially when there is no mix design to change the proportions based on the quality of aggregate. In the case of Kathmandu Valley, where aggregate is collected from several rivers with distinctly varied lithology and grading, applying a standard 1:2:3 mix ratio for all types of aggregate is scientifically inappropriate

CONCLUSION

In this study, an empirical field survey along with a controlled lab experiment and economic analysis have been carried out to determine the effects of the widely used nominal 1:2:3 concrete mix ratio on structure and economy by considering local aggregates in Kathmandu Valley. The main findings of this research are as follows:

1. The nominal volumetric batching of a 1:2:3 mix ratio for M20 concrete is practiced at 72.72% of the surveyed M20 concrete sites, and only 27.27% of total M20 sites conduct the cube test. This represents a systemic quality control gap for the most common concrete grade used in the region.
2. Under controlled laboratory conditions, field/practice mixes (1:2:3 volumetric) fail the mean strength criterion for M20 concrete under IS 456 (Bureau of Indian Standards, 2000), regardless of the type of aggregate used, despite passing the characteristic value. The likelihood of failure is much higher when these mixes are used in practical construction situations.
3. Designed mixes at a higher w/c ratio of 0.55 were

found unacceptable in either group, with their mean strength at 17.9 and 18.5 MPa, respectively. Considering that on-site water addition for improved workability is a usual practice, a significant number of on-site batches of M20 proportioned concrete in Kathmandu Valley could possibly be working at effective w/c ratios that would make them fail at this level.

4. In the limited cost range of roughly NRs 13,240 to 13,950/m^3 (range of about 5.4%), compressive strength varied between 17.9 and 36.4 MPa, which is a two-fold variation. Strength-to-cost ratio varied between 1.34 and 2.70 MPa per 1,000 NRs, and field-/practice mixes always fell at the lower end of this range. Based on this result, IS-mix design with proper control of w/c ratio is economically more advantageous than nominal batching. However, this analysis is strictly constrained to direct material cost. Their real-world economic benefit analysis requires a full field-scale life-cycle analysis taking into account other operational overheads.
5. The Dhading aggregate mix (Zone I fine aggregate, LA value 33.2%, specific gravity 2.70) was more effective than the Trishuli/Melamchi aggregate mix (Zone IV fine aggregate, LA value 36.7%, specific gravity 2.63) at equal or reduced cost. The fineness modulus variations (3.11 compared to 1.94 for fine aggregate) are considered the main reason behind this outcome, while Zone IV sand requires increased mixing water content and is not efficient in utilizing cement paste. Aggregate source and grading must be treated as primary mix design inputs, not as interchangeable background parameters.
6. Overall, the results emphasize the dire need for immediate improvement in the concrete quality management system in Kathmandu Valley, including mandatory testing for concrete manufacture, the official acceptance of IS 10262 mix design methodology for all structural concrete grades, strict monitoring of the w/c ratio at the construction site, and systematic evaluation of aggregates during the mix design procedure. While this recommendation aligns with provisions already incorporated in existing codes and standards, the central challenge in Nepal is one of implementation and enforcement rather than technical knowledge. The primary contribution of this study is to provide quantitative, locally validated evidence, through laboratory testing of Kathmandu Valley aggregates, to support the case for stricter code compliance and enforcement. By doing this, we hope to bridge the gap between existing code provisions and actual construction practice.

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