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Teaching defensible concrete selection through changing specifications and limiting margins

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ABSTRACT

Materials selection teaching should make the conditions supporting a recommendation as visible as the recommendation itself. A concrete selection exercise is developed around ingredient quantities, slump, flow, and 28-day compressive strength for 103 formulations. Learners first minimize cement content subject to simultaneous workability and strength requirements, then reconsider their answer after a requirement or a declared allowance changes. Complete enumeration identifies eligible choices, limiting inequalities, exact selection boundaries, and incompatible requirements. Under the initial brief, fifteen formulations meet the nominal limits, whereas ten satisfy allowances of 1 cm for slump, 2 cm for flow, and 2 MPa for strength. The minimum-cement choice changes from 140.2 to 160.0 kg per cubic metre. Only three of the fifteen eligible formulations remain undominated when cement content and limiting margin are considered together. Across sixty-four combinations of workability bounds and strength minima, forty-two admit a selection; omitting workability produces a nonconforming choice in thirty-five of those cases. A separate infeasibility exercise exposes a direct conflict between its slump interval and strength minimum and quantifies two possible changes to the teaching brief. Six figures, complete worked calculations, a ninety-minute lesson sequence, and an analytic assessment rubric connect the numerical treatment to classroom use. The contribution is an executable teaching technique whose numerical content is verified.

KEYWORDS

materials education; concrete selection; workability; limiting margin; guard band; assessment

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1. INTRODUCTION

Materials engineering education asks students to connect composition, processing, response, and performance in a particular application. A technically correct description of a property is only one part of that task. Students must also decide whether the property satisfies the relevant requirement, whether another property excludes the same material, and how much of the recommendation survives a change in the intended use. Contemporary discussion of undergraduate materials teaching emphasizes active participation, relevance to engineering practice, and connections across disciplinary boundaries [1, 2]. These priorities create a specific instructional challenge: a classroom activity should require a decision that can be examined and corrected, rather than merely display an attractive material or a sophisticated calculation.

Interdisciplinary materials teaching provides opportunities to connect physical measurements with environmental considerations, manufacturing restrictions, and professional judgment [3]. However, these connections can become difficult to assess if the exercise permits an answer to remain persuasive through verbal justification alone. A recommendation should have a numerical basis and a stated domain of validity. For concrete, workability and hardened strength provide a direct setting because they describe different stages of use and cannot be substituted for one another. A formulation with the largest compressive strength may be unsuitable for a designated workability window. Conversely, an easily placed material may fail a necessary strength requirement. The teaching task is to make such exclusions explicit before optimizing a preferred quantity.

Instruction in materials characterization increasingly combines the interpretation of measurements with the selection of an appropriate investigation and the development of research skills [4]. Concrete teaching has also used computed tomography to connect internal structure with macroscopic behavior [5]. These developments show the value of giving learners access to physical evidence from more than one representation. Yet a visible material image, a measurement, and a defensible selection answer serve different purposes. An image may help a student recognize a test; a value establishes a response under particular conditions; a selection requires that the value be compared with an explicit requirement. The present activity keeps these functions distinct while requiring students to move between them.

Materials training for construction further emphasizes the relationship among properties, selection, and installation [6]. Open digital tools have brought materials selection into accessible computational teaching [7]. Accessibility is valuable, but the operation performed with a tool remains decisive. Sorting a spreadsheet by the largest strength value does not establish simultaneous compliance with several conditions. Adding differently dimensioned quantities into a single score can also conceal a failure behind a favorable value elsewhere. A teaching resource therefore needs a transparent rule that separates a mandatory condition from an objective and makes an empty answer acceptable when no formulation satisfies the brief.

The educational rationale for requiring learners to act on evidence is supported by research on active learning in undergraduate science and engineering [8]. Such evidence does not justify assuming that every activity involving a spreadsheet is effective. Instructional implementation, the nature of the assessed performance, and the learners' preparation remain important. Moreover, students' sense that an activity was easy or productive need not track the amount learned [9]. A resource that generates interesting answer changes must consequently distinguish its mathematical verification from an evaluation of learning. The calculations presented here establish what the exercise contains and what its correct answers are. They do not substitute for a comparison of student performance.

The order of explanation and problem solving also requires care. Evidence on problem solving before instruction supports benefits under particular design conditions, whereas changing the order or introducing contrasting cases alone does not guarantee improvement [10, 11]. The present lesson therefore begins with explicit treatment of units, interval limits, and conjunction, followed by a short worked comparison. Students then solve a complete selection task and receive a changed requirement. This arrangement permits useful contrast without requiring novices to discover the entire selection procedure through unsupported trial and error. It also gives the instructor a way to distinguish failure to understand the rule from a correct application of the rule to an impossible brief.

Worked examples can support acquisition of procedures, although the effectiveness of additional explanation prompts depends on how they are designed [12]. The questions used here are correspondingly narrow. A learner identifies the violated inequality, computes the closest normalized limit, or explains why a particular earlier choice is excluded. The request is not an unrestricted account of everything that might affect concrete performance. A useful written explanation links a specific quantity to a specific consequence. Research comparing explanation activities likewise cautions against treating all forms of explaining as interchangeable [13]. The exercise uses short numerical justifications so that reasoning can be examined without allowing writing fluency to dominate the task.

Concrete selection also offers a disciplined way to discuss uncertainty. A measurement close to a limit can satisfy a nominal requirement while offering little allowance for variation. The relevant question is not whether one candidate is "more reliable" in an unspecified sense, but how far each required response lies from its limiting value under a

declared rule. Modern concrete design under uncertainty connects material decisions to structural consequences and distinguishes several kinds of incomplete knowledge [14]. In the present activity, allowances are assigned for teaching. Their algebraic implications can be calculated exactly, but their magnitudes are not estimated from replicated tests. Maintaining that distinction allows students to learn a useful reasoning operation without mistaking an assumed bound for a probability.

The objective of reducing cement content is similarly precise. Cement demand and concrete production have environmental consequences, but an environmental comparison requires more information than cement mass alone [15]. The exercise therefore minimizes the recorded cement quantity while retaining the other composition values and performance requirements. It does not convert cement reduction into an unmeasured reduction in emissions or cost. This restriction is educationally useful: learners must identify which claim follows from the available quantities and which claim would require further evidence. Their answer can be economical with cement under an assigned brief without being a complete assessment of environmental performance.

The contribution is a teaching technique in which each recommendation must be accompanied by the condition that would invalidate it. The same formulations are examined under changing strength or flow requirements, under progressively larger allowances, and under a brief with incompatible conditions. Exact enumeration supplies an instructor answer key, while a dominance calculation reduces the admissible choices to the formulations that can matter when cement and limiting margin are considered together. A requirement map shows where selection changes, and an intersection analysis distinguishes separate positive counts from a jointly feasible material. The central educational performance is thus a defensible selection followed by a defensible revision or refusal to select. The paper develops the calculation, examines the resulting choices, and integrates the learner prompts, worked answers, and assessment criteria into the teaching sequence.

2. MATERIAL QUANTITIES AND DECISION CONDITIONS

2.1. Measurements and their physical interpretation

The concrete measurements comprise seven ingredient quantities and three responses for 103 distinct formulations. Cement, slag, fly ash, water, superplasticizer, coarse aggregate, and fine aggregate are expressed as mass per unit concrete volume. Slump and flow are expressed as lengths, and compressive strength refers to 28 days [16]. Each formulation retains its numerical identifier so that the worked answers can be checked against the cited measurements. Zero slump observations are retained; missing values and repeated complete entries are absent. Table 1 gives the actual ranges and units.

Table 1: Measured quantities available for every formulation. Ingredient masses refer to one cubic metre of concrete; strength is at 28 days.

Quantity	Unit	Minimum	Maximum
Cement	$\mathrm{kg\,m^{-3}}$	137.0	374.0
Slag	$\mathrm{kg\,m^{-3}}$	0.0	193.0
Fly ash	$\mathrm{kg\,m^{-3}}$	0.0	260.0
Water	$\mathrm{kg\,m^{-3}}$	160.0	240.0
Superplasticizer	$\mathrm{kg\,m^{-3}}$	4.4	19.0
Coarse aggregate	$\mathrm{kg\,m^{-3}}$	708.0	1049.9
Fine aggregate	$\mathrm{kg\,m^{-3}}$	640.6	902.0
Slump	cm	0.0	29.0
Flow	cm	20.0	78.0
Compressive strength	MPa	17.19	58.53

Slump describes a vertical change after removal of the mold, whereas flow describes the lateral extent of the deposited material. The two observations are related to fresh-state behavior but do not measure identical geometrical features. Figure 1 presents separate instructional views of these geometries. The images are computer-generated illustrations and do not depict the tested formulations. Their role is recognition of the observation, not validation of a numerical value or demonstration of a test standard. The applicable measurement procedures distinguish the slump of

hydraulic-cement concrete from the slump flow of self-consolidating concrete [17, 18]. The historical flow values are retained under their given designation; they are not retroactively assigned to a different procedure.

Recent rheological investigation of the slump test examines how deposit form relates to yield stress and viscosity, which reinforces the need to distinguish an observation from a complete rheological characterization [19]. A broader treatment of fresh concrete also includes structural build-up, thixotropy, and flow resistance [20]. The present three-response selection exercise does not estimate these additional properties. In particular, a passing flow value is not taken as evidence of adequate segregation resistance or pumpability. The physical interpretation remains tied to the response and the requirement assigned to it.



(a) Vertical drop.

(b) Lateral footprint.

Figure 1: Two geometries used when discussing fresh-concrete workability.

The seven component quantities likewise describe composition without determining every aspect of behavior. Superplasticizer chemistry and dosage can affect dispersion and fresh-state response, while rheology-modifying admixtures act through interactions that depend on material and test conditions [21, 22]. Measurement of fresh cement paste introduces further procedural considerations, including the selection of a suitable rheological method [23]. Consequently, the total superplasticizer mass is retained as an ingredient quantity; it is not interpreted as an interchangeable amount of a particular modern polymer or as proof of a common rheological state across formulations.

Slag and fly ash are included in the binder total for the compositional comparison. Their effects on hydration, durability, and shrinkage depend on their characteristics and on the surrounding cementitious system [24, 25]. The available information does not identify all such characteristics or establish common batching and testing conditions. It also does not identify independent production batches or replicate measurements. Recipe uniqueness therefore supports a finite list of distinct alternatives, but it does not establish statistical independence or repeatability. The calculations answer a finite selection question and make no estimate of a population mean, causal ingredient effect, or production failure probability.

2.2. Teaching briefs and the finite selection question

A brief specifies an acceptable slump interval, an acceptable flow interval, and a minimum strength. These are assigned teaching requirements, not construction acceptance criteria. Brief A (Table 2) requires slump from 15 to 25 cm, flow from 45 to 65 cm, and strength of at least 35 MPa. Brief B changes only A's strength minimum to 45 MPa. Brief C returns to A and changes only its flow minimum to 55 cm. Brief D requires slump from 15 to 20 cm, flow from 60 to 65 cm, and strength of at least 45 MPa. Each interval includes its endpoints.

The formulations are assessed as, without interpolating a new composition or fitting a property predictor. This differs in scope from concrete proportioning problems that seek an untested mixture through mathematical programming or machine learning. Operational research in concrete mixture design addresses several performance and resource requirements, making the separation of constraints and objectives especially important [26]. Here,

complete enumeration is practical and keeps every exclusion traceable to a number. The small finite choice set is an instructional advantage: a learner can verify the selected candidate without accepting the internal operation of a search algorithm.

Cement content is minimized only after all requirements are satisfied. A formulation with a lower cement quantity is not preferred if it violates a compulsory limit. Equal cement quantities are resolved by higher recorded strength and then by the smaller identifier. This final convention makes repeated calculations deterministic without giving the identifier a physical meaning. When no formulation meets the brief, the correct computational answer is an empty feasible set. Any subsequent alteration belongs to a separately authorized change of the teaching requirements.

3. SELECTION, ALLOWANCES, AND VERIFICATION

3.1. Eligibility and the objective

For formulation i, let s_i denote slump, q_i flow, f_i strength, and c_i cement content. Lower and upper workability limits are L_s, U_s, L_q, U_q, and the minimum strength is L_f. The set of eligible alternatives is

$$\mathcal{F} = \{i : L_s \le s_i \le U_s, \quad L_q \le q_i \le U_q, \quad f_i \ge L_f\}. \tag{1}$$

The recommendation follows from

$$i^* = \arg\min_{i \in \mathcal{F}} c_i, \tag{2}$$

with the stated tie-breaks. An empty $\mathcal{F}$ produces no recommendation. Eq. (1) is a conjunction: compensation among requirements is excluded. This feature is retained in both the lesson and its marking criteria.

3.2. Limiting normalized margin

The assigned allowances are $\delta_s = 1$ cm, $\delta_q = 2$ cm, and $\delta_f = 2$ MPa. They supply a common dimensionless measure of distance from the five limits. Their magnitudes are teaching assumptions; they have not been obtained from calibration, repeated specimens, or a production distribution. For each formulation,

$$\rho_i = \min\left\{\frac{s_i - L_s}{\delta_s}, \frac{U_s - s_i}{\delta_s}, \frac{q_i - L_q}{\delta_q}, \frac{U_q - q_i}{\delta_q}, \frac{f_i - L_f}{\delta_f}\right\}. \tag{3}$$

A negative value identifies a failure, zero identifies a boundary, and a positive value identifies clearance from every limit. The minimizing term identifies the controlling requirement. A mean of the five terms would answer a different question because positive values could conceal a negative one.

For a multiplier $k \ge 0$, the guarded choice set is

$$\mathcal{F}(k) = \left\{\begin{array}{c} L_s + k\delta_s \le s_i \le U_s - k\delta_s, \\ i : L_q + k\delta_q \le q_i \le U_q - k\delta_q, \\ f_i \ge L_f + k\delta_f \end{array}\right\}. \tag{4}$$

Eqs. (3) and (4) give $i \in \mathcal{F}(k)$ exactly when $\rho_i \ge k$. If actual deviations were bounded by the assigned allowances multiplied by k, membership would preserve the assigned requirements under those deviations. This conditional statement does not estimate how frequently such bounds hold. A minimum margin is thus a deterministic sensitivity quantity, not a confidence level.

3.3. Dominance, incompatible conditions, and dimensional checks

Among nominally eligible formulations, j dominates i in the cement–margin comparison when $c_j \le c_i$ and $\rho_j \ge \rho_i$, with at least one strict inequality. A strictly higher-cement dominated alternative cannot improve the least-cement choice as k increases. Alternatives with equal cement retain the stated tie-breaks when determining the selected path. The undominated alternatives identify the attainable cement–margin trade-off. Exact boundary values are calculated from the recorded decimal quantities. Equality preserves eligibility, so a candidate is excluded immediately above its limiting value, not at that value.

For an empty brief, the three response conditions are also evaluated separately and in every exclusive intersection. This identifies whether the conflict involves workability alone, strength together with one workability condition, or the full combination. A separate calculation asks whether changing exactly one bound can admit a candidate while all other inequalities remain fixed. These changes describe the teaching brief mathematically; their size does not establish practical permission to weaken a requirement.

Every formulation is assessed under each of the four briefs. A broader comparison combines four slump intervals, four flow intervals, and four strength minima, giving sixty-four prescribed combinations. The slump intervals are $[0, 10]$, $[10, 20]$, $[15, 25]$, and $[20, 29]$ cm; the flow intervals are $[20, 40]$, $[35, 55]$, $[45, 65]$, and $[55, 78]$ cm; the strength minima are 30, 35, 40, and 45 MPa. This gives 6,592 nominal eligibility decisions. A deliberately incomplete rule minimizes cement after applying only the strength requirement. Its answer is then checked against the omitted workability limits. The resulting frequency measures that particular omission over the prescribed combinations, not a distribution of student errors.

A separate calculation repeats the counts and selections using explicit comparisons. The four briefs are also recalculated after twenty order changes at both $k = 0$ and $k = 1$, producing 160 order-invariance checks. Finally, slump, flow, their bounds, and their allowances are consistently converted from centimetres to millimetres. This transformation must preserve membership and the ratios in Eq. (3). No statistical significance test is applied because the question concerns the complete finite choice set, not an independent sample of teaching briefs.

4. RESULTS AND DISCUSSION

4.1. Initial selection and the cost of ignoring a limit

Brief A admits fifteen formulations. The least-cement choice is mixture 84, containing 140.2 $\mathrm{kg\,m^{-3}}$ cement, with slump 21.25 cm, flow 46.0 cm, and strength 36.32 MPa. Its eligibility is established by comparing each observation with the appropriate bound, not by its position in a strength ranking. The two interval checks represent four inequalities, and the strength comparison supplies the fifth. This distinction matters when assessing a learner's calculation: writing only "workability acceptable" does not reveal whether both endpoints were considered.

The strongest formulation, mixture 49, reaches 58.53 MPa but has slump 0 cm and flow 20 cm. It fails both lower workability requirements in A. Its high strength is therefore irrelevant to the choice defined by Eq. (2). This contrast is useful because the excluded response is genuinely favorable in one respect. The error is not a failure to recognize strength; it is a failure to apply the other compulsory conditions. An instructor can thus ask a learner to identify the precise reason that a seemingly impressive measurement does not settle the engineering question.

The normalized clearances of mixture 84 are 6.25 for the lower slump limit, 3.75 for the upper slump limit, 0.50 for the lower flow limit, 9.50 for the upper flow limit, and 0.66 for the strength minimum. The smallest value belongs to flow. A statement based only on positive strength clearance would consequently identify the wrong controlling requirement. Figure 2 displays the separate terms alongside those for mixture 67. Presenting the terms individually preserves the physical origin of the minimum and prevents the dimensionless result from becoming an unexplained score.

At the full allowance level, ten formulations remain eligible and mixture 67 is selected. Its cement content is 160.0 $\mathrm{kg\,m^{-3}}$, with slump 18.0 cm, flow 48.0 cm, and strength 37.66 MPa. The governing normalized clearance is 1.33, now associated with strength. The controlling requirement has changed as well as the selected formulation. The cement difference is 19.8 $\mathrm{kg\,m^{-3}}$, corresponding to 14.1% of the nominal selection's cement content. This calculation quantifies a material quantity sacrificed to obtain additional clearance under the assigned rule. It does not attach a price or an emission factor to that difference.

The change also illustrates why nominal and guarded eligibility should be taught as distinct questions. Mixture 84 is not an incorrect answer to A at zero allowance. It is an incorrect answer to the same brief once the required multiplier exceeds its limiting clearance. A student who replaces the nominal answer without explaining the altered

condition has completed only part of the reasoning task. The complete response identifies which version of the brief is being solved and states why the earlier recommendation is no longer admissible.

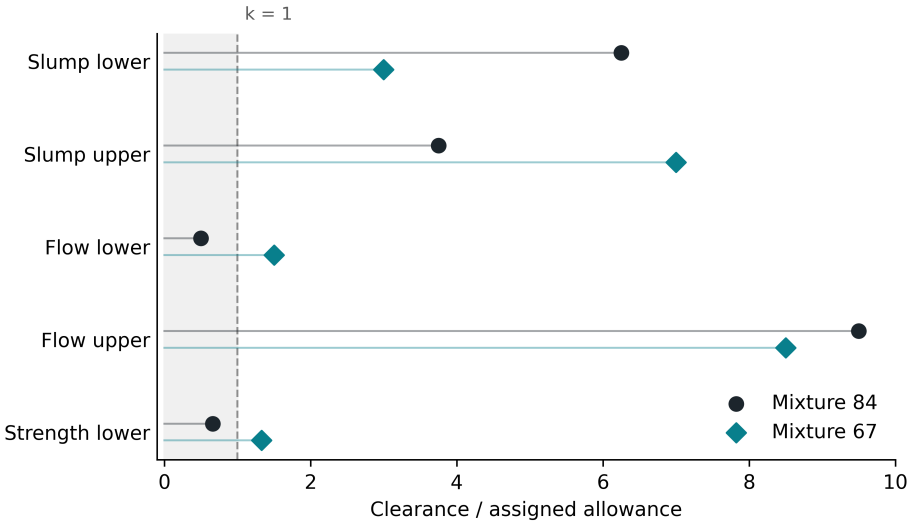


Figure 2: Separate normalized clearances for the nominal and guarded selections under brief A.

4.2. Selection boundaries under changed strength and flow

Increasing the strength requirement in B leaves five nominally eligible formulations. Mixture 19 minimizes cement among them and is also the only formulation satisfying the full assigned allowance. Its cement quantity is 310.0 $\mathrm{kg\,m^{-3}}$, with slump 20.5 cm, flow 48.2 cm, and strength 49.30 MPa. The initial selection is excluded because its strength is below the new minimum; its workability observations remain unchanged. Holding the workability requirements fixed makes this a controlled change in the decision rule, although it is not a controlled laboratory comparison of compositions.

Increasing only the flow minimum in C leaves seven nominal alternatives. Mixture 48 is selected at 287.0 $\mathrm{kg\,m^{-3}}$ cement. Its flow and strength satisfy the brief, but its slump is exactly the upper limit. Accordingly, its limiting margin is zero: it supports nominal selection and no positive allowance. With the full allowance, four choices remain and mixture 54 minimizes cement at 309.0 $\mathrm{kg\,m^{-3}}$. Its slump of 24 cm places the upper slump bound in control. This second change demonstrates that a condition other than the deliberately altered requirement can ultimately limit the replacement choice.

The requirement plane in Figure 3 extends this comparison while fixing slump at 15–25 cm and the upper flow limit at 65 cm. Each location specifies a minimum flow and minimum strength. The colored region identifies the minimum-cement formulation under those requirements. Nine different identifiers occur over the displayed range. The plot is calculated by direct comparisons on a fine display grid; it does not fit a response surface or estimate the performance of an untested composition. Exact checks remain necessary at boundaries because the inequalities are inclusive.

The region occupied by mixture 84 is restricted by both its flow and strength. Raising either minimum sufficiently removes it, but the replacement depends on the direction of change. A requirement near the lower-left corner of the map may permit a low-cement, high-fly-ash formulation, whereas a higher strength minimum can select a substantially larger cement quantity. These are changes in admissibility within the alternatives. They should not be interpreted as a continuous prescription for increasing cement to obtain a specified strength.

For teaching, the map supports a question that is more demanding than reading a candidate value: how far can the brief move before the present answer loses eligibility, and what determines the next answer? A learner can trace the relevant limits and then test a neighboring requirement. This moves attention from memorizing one selected identifier to understanding the conditional nature of selection. The interpretation remains local to the

stated cement objective and workability interval. A different objective or an additional compulsory property would require a different map.

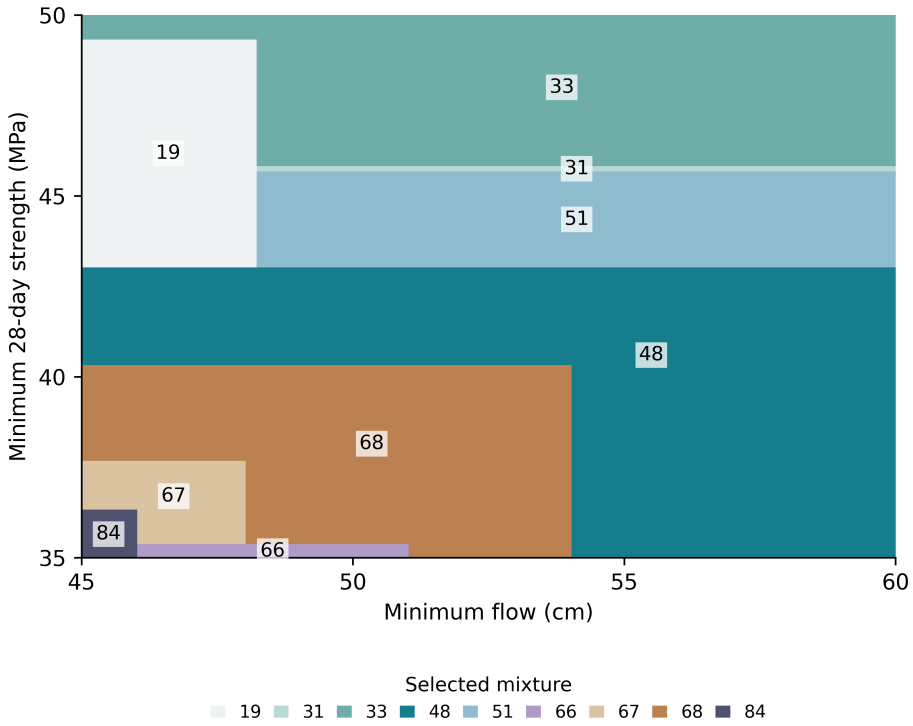


Figure 3: Ownership of the least-cement recommendation as the minimum flow and strength change.

Table 2: Assigned briefs and computed choices.

	Slump	Flow	Strength	Eligible		Selected mixture	
Brief	cm	cm	MPa	Nominal	Guarded	Nominal	Guarded
A	15–25	45–65	≥ 35	15	10	84	67
B	15–25	45–65	≥ 45	5	1	19	19
C	15–25	55–65	≥ 35	7	4	48	54
D	15–20	60–65	≥ 45	0	0	–	–

4.3. Successive exclusions and the sixty-four combinations

The attrition of alternatives is physically interpretable when each condition is displayed separately. In A and B, the slump interval admits sixty-two formulations and the joint workability window admits forty-seven. Adding the strength condition leaves different final counts even though the first two filters are identical. In C, the higher flow minimum reduces the joint workability count to twenty-five before strength is applied. Figure 4 makes these distinct contributions visible. The final intersection is independent of filter order, although intermediate counts would change if the order were reversed.

The broader set of sixty-four combinations contains forty-two feasible choices and twenty-two empty sets. The strength-only rule returns a workability-nonconforming selection in thirty-five feasible combinations. Its success in the remaining seven cases does not validate the omitted filters; it means that the selected formulation happened to satisfy them. This is a useful teaching distinction between a justified procedure and a coincidentally correct identifier. A learner who omits workability can occasionally arrive at the same identifier as the complete procedure while still providing an incomplete argument.

The percentage associated with this omission is 83.3% of feasible combinations. It should not be interpreted as an expected classroom error rate, a practical failure probability, or a general property of concrete design. The intervals overlap, their values were prescribed for the teaching comparison, and each combination gives equal weight to a

different brief. A new set of bounds could change the percentage. The informative result is that the omission creates many concrete counterexamples whose causes can be inspected, while the denominator remains explicitly defined.

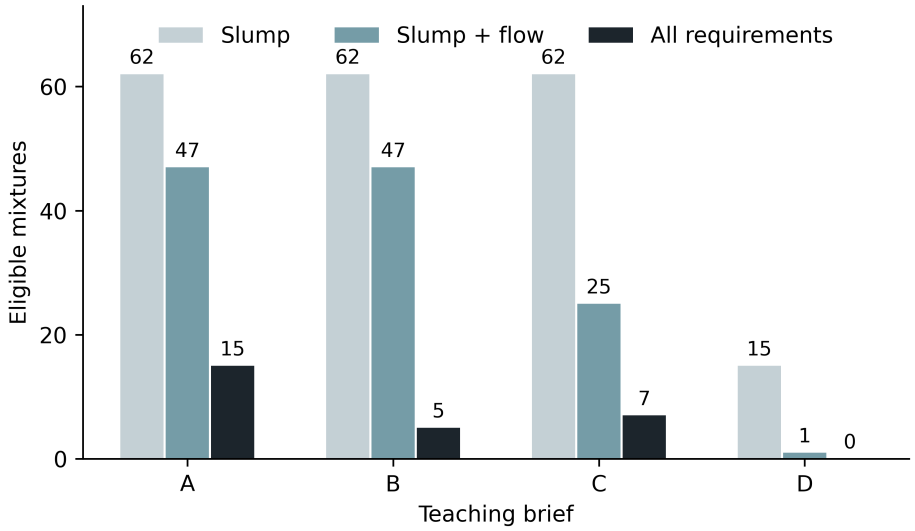


Figure 4: Alternative counts after the slump condition, joint workability conditions, and all requirements.

Introducing the full allowance leaves thirty-three feasible combinations. Nine combinations that admit a nominal choice become empty, equivalent to 21.4% of the nominally feasible group. This observation gives an additional role to an empty answer: it can arise after allowances are imposed even when nominal selection was possible. The correct response is to identify the changed decision condition and its consequence. Automatically returning to the nominal answer would quietly abandon the allowance requirement and obscure why it had been introduced.

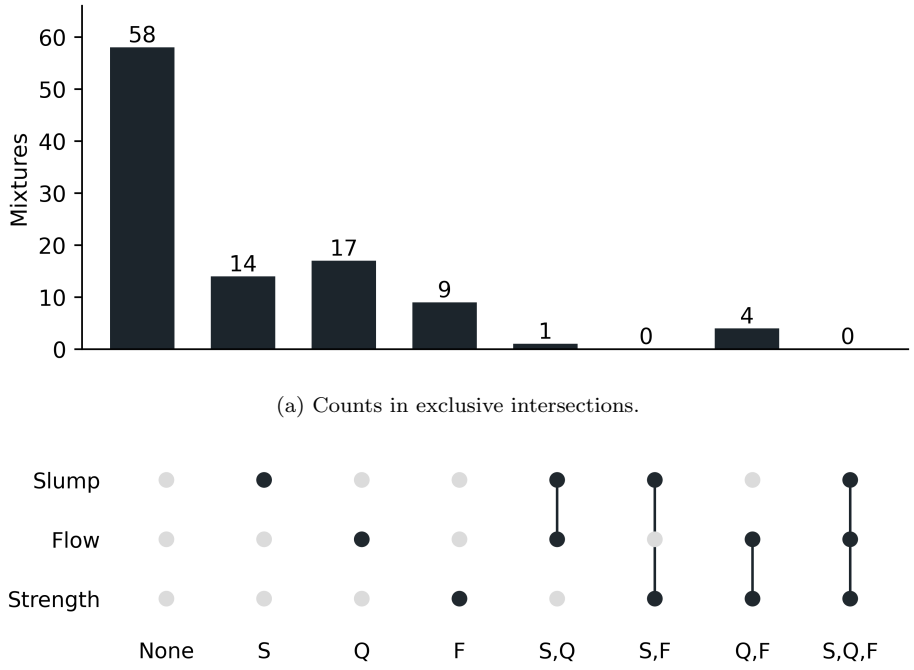
The independent comparison calculation matches all sixty-four nominal counts and selections. The order changes preserve the answers in all 160 checks. Consistent conversion of the workability quantities and bounds to millimetres also preserves every nominal membership decision. These results test implementation consistency rather than the truth of an assumed physical model. They are especially useful in a teaching resource because an incorrect software answer could otherwise be mistaken for a difficult materials principle.

4.4. An incompatible brief and the meaning of a repair

Brief D is empty even though its three conditions individually admit positive numbers of alternatives. Fifteen formulations satisfy the slump interval, twenty-two satisfy the flow interval, and thirteen reach the strength minimum. Only mixture 5 satisfies both workability intervals, and its strength is 26.82 MPa. The fact that separate acceptable groups exist is therefore insufficient. Eligibility requires that the same formulation belong to all three groups.

The exclusive intersections in Figure 5 locate the conflict more precisely. No formulation satisfies the slump interval together with the strength minimum, regardless of flow. The largest strength among those inside the slump interval is 43.95 MPa. Thus, the pair comprising slump and strength is already incompatible within the alternatives. The flow condition further restricts workability, but it is not needed to prove that the complete brief is empty. A learner can establish infeasibility through this smaller contradictory pair instead of repeatedly testing every condition on every candidate.

Changing a single bound provides two mathematically distinct ways to admit a alternative. Raising the upper slump bound from 20 to 20.5 cm admits mixture 55 while preserving the flow and strength requirements. Its flow is 61.5 cm, strength 45.42 MPa, and cement content 322.0 $\mathrm{kg\,m^{-3}}$. Alternatively, retaining the complete workability window requires lowering the strength minimum to 26.82 MPa so that mixture 5 becomes eligible. This is a decrease of 18.18 MPa. The alternatives are changes to different requirements and should not be described as equally acceptable engineering repairs.



(a) Counts in exclusive intersections.

(b) Conditions defining each column.

Figure 5: Exclusive response-condition membership for brief D.

The first alteration is 0.50 of the assigned slump allowance, whereas the strength alteration is 9.09 assigned strength allowances. Normalization makes these magnitudes comparable under the classroom convention, but it does not establish the consequences of accepting either change. A strength requirement may reflect a structural necessity that cannot be relaxed, and an upper slump limit may reflect a separate placement or stability restriction. The exercise should therefore end with a request for the authority or evidence needed to change the brief, rather than an automatic preference for the numerically smaller alteration.

Relaxing either flow bound alone cannot remove the slump–strength incompatibility. Lowering the slump minimum alone also cannot admit the four formulations that meet the existing flow and strength requirements because their slump values all exceed the upper bound. This gives students a practical way to reject an ineffective change before performing a complete recalculation. The strongest conclusion remains finite: none of the alternatives meets the original brief. The calculation does not prove that an untested composition could never satisfy it.

4.5. Exact allowance boundaries and undominated alternatives

Under A, only mixtures 84, 67, and 68 are undominated in the cement–margin comparison. Twelve nominally eligible alternatives are dominated. Their exclusion from the efficient set does not mean that they are defective materials; it means that another formulation has no greater cement content and at least as much limiting clearance under this brief. For the stated objective and allowance rule, retaining those twelve alternatives cannot improve the selected answer.

Mixture 84 is selected through a multiplier of 0.50, including equality. Immediately above that value, mixture 67 becomes the least-cement admissible choice and remains so through 1.33. Mixture 68 then governs through 2.67, above which A has no eligible formulation. The last alternative contains 166.0 $\mathrm{kg\,m^{-3}}$ cement and reaches 40.34 MPa. Its controlling term is again strength. Thus, a modest further increase in cement can support a substantially larger assigned multiplier, but only because the particular responses provide that clearance.

Under B, mixture 19 is the sole undominated alternative and remains selected through 1.60. Under C, four formulations are undominated. Mixture 48 is selected only at zero allowance; mixture 54 governs immediately above zero through 1.00; mixture 51 governs immediately above 1.00 through 1.50; and mixture 55 governs immediately above

1.50 through 1.75. Table 3 lists these exact intervals. The distinction between inclusive endpoints and exclusion immediately above them is necessary for a correct answer to a question about the largest admissible allowance.

Table 3: Least-cement choices along the exact allowance paths.

Brief	Mixture	Cement ($kg\,m^{-3}$)	ρ	Selected interval	Controlling limit
A	84	140.2	0.50	$0 \le k \le 0.50$	Flow lower
A	67	160.0	1.33	$0.50 < k \le 1.33$	Strength lower
A	68	166.0	2.67	$1.33 < k \le 2.67$	Strength lower
B	19	310.0	1.60	$0 \le k \le 1.60$	Flow lower
C	48	287.0	0.00	$k = 0$	Slump upper
C	54	309.0	1.00	$0 < k \le 1.00$	Slump upper
C	51	320.0	1.50	$1.00 < k \le 1.50$	Slump upper
C	55	322.0	1.75	$1.50 < k \le 1.75$	Flow upper

These finite transitions provide a stronger teaching object than a general statement that a larger allowance is more demanding. A learner can identify the exact invalidating condition, name the replacement, and determine when no replacement exists. The operation remains transparent because every event is tied to one quantity and one stated bound. There is no justification for interpolating a formulation between neighboring identifiers or for treating the selection changes as discontinuities in concrete behavior. They are discontinuities in which of the alternatives solves a changing decision problem.

Efficient-set reduction has a direct justification that can itself become a teaching question. Suppose one formulation requires less cement than another and has an equal or larger limiting margin. Every allowance level admitting the second formulation also admits the first. Selecting the second cannot then minimize cement. The conclusion concerns a pair of numerical inequalities; it makes no assertion about hydration, particle packing, or long-term behavior. If cement quantities are equal, the selected identifier still depends on the declared strength and identifier tie-breaks. An efficient-set calculation must therefore be distinguished from the complete deterministic selection rule.

The boundary calculation also permits an exact distinction between losing a recommendation and losing every admissible choice. At the first transition in A, the initial formulation becomes ineligible immediately above its limiting multiplier, but two efficient alternatives remain. At the last transition, no replacement survives. These events deserve different explanations. The first calls for a justified replacement under the existing rule; the second calls for an empty answer and a discussion of what additional evidence or authorized alteration would be necessary. Treating both events simply as a worse score would conceal their different implications. The finite calculation thus supports an assessment of conditional reasoning without requiring a statistical model of unobserved concrete performance.

4.6. Binder allocation and the limits of compositional explanation

Figure 6 places the highlighted formulations in cement–slag–fly-ash coordinates after dividing each binder component by the binder total. Mixture 84 contains 409.7 $kg\,m^{-3}$ binder, with cement accounting for 34.22%, slag for 7.44%, and fly ash for 58.34%. Mixture 67 has an almost identical total binder quantity but a different allocation: 39.02% cement and 60.98% fly ash, without slag. The nominal cement saving is therefore not simply a saving in total binder. This distinction is easy to miss if an instructional discussion uses “cement” and “binder” interchangeably.

Mixtures 19, 54, and 55 occupy nearly coincident binder-fraction positions, yet their strengths are 49.30, 38.59, and 45.42 MPa, respectively. Their water contents, aggregate quantities, and other responses differ. The near coincidence is consequently a useful caution against explaining the selection entirely through binder fractions. The triangle is a compositional projection, not a causal model. Table 4 retains the other ingredient quantities so that the projection can be interpreted without discarding the surrounding material information.

Fly ash can affect several fresh and hardened properties, with outcomes depending on characteristics and replacement conditions [27]. The wider range of available supplementary cementitious materials introduces additional

differences in composition, reactivity, and practical suitability [28]. The observed choices should therefore be used to teach conditional material interpretation rather than a universal statement that a particular replacement fraction determines a response. Their physical value is that several ingredient combinations can satisfy one brief, while a changed brief selects a different combination.

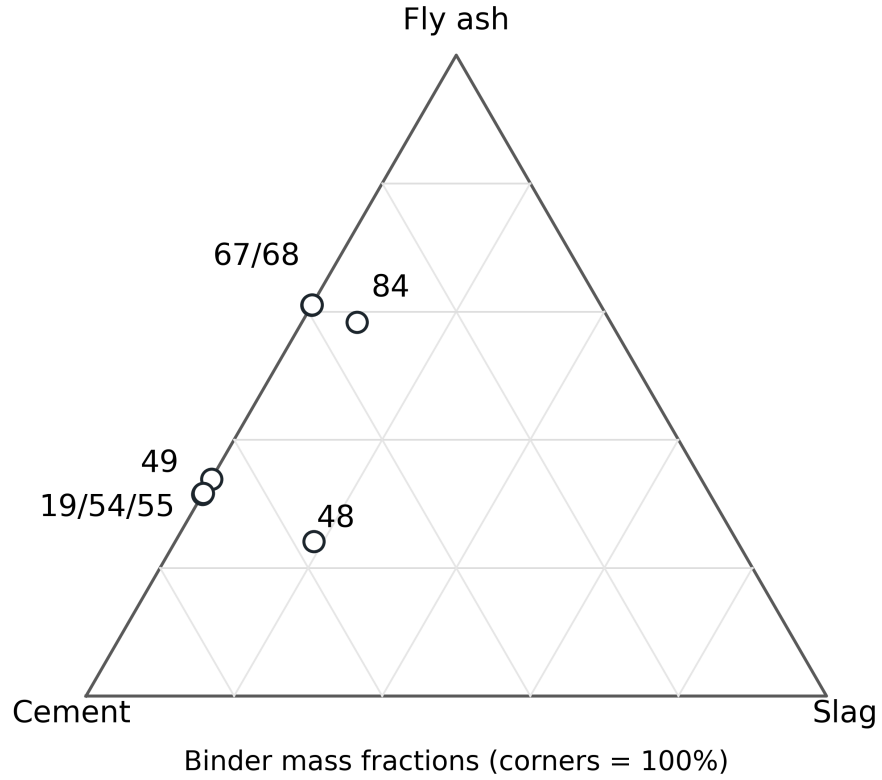


Figure 6: Binder allocation in the highlighted selections and the strongest formulation.

Environmental interpretation requires similar restraint. Cement-related comparisons can depend on system boundaries and uncertain emission factors, and these choices can alter the preferred structural design [29]. The present objective establishes only a minimum recorded cement quantity subject to the assigned-response limits. An environmental assessment would additionally require constituent production, transport, allocation, service life, and relevant structural consequences. Keeping the narrower statement precise makes the activity suitable for a later connection to sustainability teaching without assigning environmental outcomes that have not been calculated.

Table 4: Ingredient quantities and responses for the highlighted alternatives.

Quantity	84	67	68	19	48	54	55	49
Cement	140.2	160.0	166.0	310.0	287.0	309.0	322.0	332.0
Slag	30.5	0.0	0.0	0.0	94.0	0.0	0.0	0.0
Fly ash	239.0	250.0	260.0	143.0	121.0	142.0	149.0	170.0
Water	169.4	168.0	183.0	168.0	188.0	218.0	186.0	160.0
Superplasticizer	5.3	12.0	13.0	10.0	9.0	10.0	8.0	6.0
Coarse aggregate	1028.4	1049.0	859.0	914.0	904.0	912.0	951.0	900.0
Fine aggregate	742.7	688.0	827.0	804.0	696.0	680.0	709.0	806.0
Slump (cm)	21.25	18.0	21.0	20.5	25.0	24.0	20.5	0.0
Flow (cm)	46.0	48.0	54.0	48.2	61.0	62.0	61.5	20.0
Strength (MPa)	36.32	37.66	40.34	49.30	43.01	38.59	45.42	58.53

5. TEACHING SEQUENCE AND ASSESSMENT

5.1. Preparation and the ninety-minute lesson

The activity is intended for undergraduate materials or civil engineering teaching after an introduction to concrete ingredients, workability observations, strength, and units. It requires the formulation quantities and a spreadsheet capable of applying simultaneous filters. A short script may perform the same comparisons, but software operation is subordinate to explaining the inequalities. The instructor first demonstrates one eligible and one excluded alternative so that subsequent difficulty concerns selection reasoning rather than unfamiliar syntax. The complete treatment of A in the results provides the worked example and answer key.

The first fifteen minutes address the meaning and units of the quantities. Learners distinguish cement from total binder, vertical slump from lateral spread, and a strength from a minimum requirement. They also identify which test conditions are unknown. The next twenty minutes address nominal selection under A. Each pair must retain the complete eligible group, identify its minimum-cement member, and write the inequalities supporting that choice. Giving the correct identifier without these comparisons is treated as incomplete work. This requirement exposes accidental agreement with the answer key and creates a checkable basis for later discussion.

The following fifteen minutes divide the class between B and C. Each pair states exactly which requirement changed and identifies the measurement that excludes its earlier answer. Another fifteen minutes introduces the normalized margins and asks pairs to solve A and their assigned change at the full allowance. The comparison must name both the replacement and its controlling limit. During the next fifteen minutes, D asks every pair to investigate an empty answer. Learners examine exclusive intersections, locate the incompatible slump–strength pair, and consider which single change could admit a formulation. The final ten minutes contain the unit conversion and an individual explanation of the limits on practical interpretation.

The ninety-minute duration is a teaching allocation, not an observed completion time. Instructors can separate nominal filtering and allowance reasoning into two classes if preparation is limited. Reviews of experiential engineering education emphasize the need to connect activity with interpretation and evaluation, rather than equate experience with action alone [30]. Accordingly, every stage here ends with a reasoned statement about a material choice. The computer-generated images support recognition of measurement geometry, while the calculation supplies the quantitative task. Neither component constitutes hands-on batching, placement, curing, or testing competence.

The exercise is also smaller in scope than a project in which students define requirements, design and manufacture a material, and evaluate its use. Research on projects in higher education distinguishes several outcomes and assessment approaches, which cautions against using successful completion of a calculation as evidence of broad design competence [31]. The four briefs can be embedded in such a project as an early selection activity. They should retain their explicit decision conditions so that a later discussion of cost, durability, or environmental consequences adds evidence and requirements rather than quietly changing what the first answer meant.

5.2. Integrated learner prompts and worked responses

The central nominal prompt asks: which formulation uses the least cement while meeting every requirement in A, and why is the strongest formulation not selected? A complete response gives mixture 84, checks its two workability intervals and strength inequality, and identifies the failed lower workability limits of mixture 49. The paired change asks whether the same answer survives B or C. The correct response excludes it by strength in B and by flow in C, then identifies mixtures 19 and 48, respectively. These responses connect a change in a requirement to a change in admissible material without invoking an unmeasured physical alteration.

The allowance prompt asks which of the five normalized clearances controls the nominal answer and which formulation should be selected when the full allowance is required. For A, the nominal answer is controlled by lower flow, whereas the guarded answer is controlled by strength. A further question asks for the largest admissible multiplier and whether equality is permitted. Table 3 supplies the complete worked answer. Asking for the invalidating con-

dition prevents learners from treating an identifier as a timeless recommendation and permits the same reasoning to be transferred to a different brief.

The infeasibility prompt asks why three nonempty individual filters do not establish a feasible formulation. Learners must refer to membership of the same alternative in the intersection. They can support the empty result using either the sole joint-workability candidate and its failed strength or the absence of any slump–strength member. The repair question then asks which existing requirement would have to change, by how much, and who could authorize it. This keeps the task connected to professional responsibility. Challenge-based engineering education involves alignment between the difficulty of a challenge and the supporting learning activities; the present brief is deliberately bounded so that its mathematical contradiction can be resolved without pretending to settle every practical design issue [32].

The final individual prompt converts the workability quantities, their bounds, and their allowances to millimetres and asks why the selection remains unchanged. A correct explanation identifies cancellation of the length conversion in the normalized ratios. Students then distinguish the assigned allowance from a uncertainty and name the further measurements needed to estimate actual variability. Closing with an individual question prevents a pair's shared calculation from being the only evidence of each learner's understanding. Retrieval research supports the use of brief recall and application checks, although it does not establish an effect for this particular concrete activity [33, 34].

5.3. Assessment and targeted feedback

Table 5 separates five aspects of performance, each scored from zero to two. The criteria concern complete eligibility, the cement objective, limiting-margin reasoning, dimensional consistency, and the scope of the conclusion. Rubrics can help make performance expectations explicit, but their effects vary and do not remove the need to examine validity in the intended task [35]. Here, the marking categories follow the operations that the exercise requires. It has not been tested for agreement among markers or for its relationship to later engineering performance.

Table 5: Analytic assessment criteria. Each row receives zero for absent or incorrect reasoning, one for a partially correct account, and two for the complete evidence specified. The maximum is ten points.

Criterion	Evidence required for two points
Eligibility	All five inclusive inequalities are checked; a favorable value cannot compensate for a failure.
Selection objective	Minimum cement is established within the complete eligible group, with the stated tie-break when needed.
Limiting margin	The normalized minimum, its controlling physical requirement, and the invalidating multiplier are identified.
Dimensional consistency	Measurements, bounds, and allowances are converted together; eligibility and normalized clearances are unchanged.
Scope of conclusion	Empty results are restricted to the alternatives; assigned allowances are distinguished from estimated production uncertainty.

Peer checking is used after each pair has committed to its own answer. The checking pair identifies the earliest unsupported step and requests a correction with the relevant quantity and bound. Evidence on peer assessment supports its potential educational value, but that evidence does not make every exchange useful [36]. A response such as "consider workability" is too broad for this task. A response naming the lower flow condition and the flow is actionable and leaves the learner responsible for recalculating the answer. The instructor can then distinguish arithmetic difficulty from a misunderstanding of conjunction or of the objective.

Feedback likewise targets the decision process rather than praise for selecting a particular identifier. Educational feedback varies in its effectiveness according to its content and purpose [37]. Digitally delivered feedback also depends on the relation among the task, the feedback focus, and learner control [38]. A spreadsheet can therefore reveal which inequality failed after a learner has submitted an answer, while requiring the learner to explain the

exclusion. Automatically displaying the replacement identifier before this explanation would remove the reasoning step that the activity is designed to assess.

Learners retain their earlier and later answer statements during the changes of brief. This allows them to inspect what was preserved, what changed, and which measurement caused the change. Research on monitoring tools supports attention to both learning content and learning behavior [39]. Self-assessment should nevertheless remain distinct from assigning one's own final mark [40]. The useful question is whether the learner can find an unsupported claim in the earlier answer and correct it with evidence. Confidence without the supporting inequality is insufficient, just as a plausible-looking plot is insufficient without the correct units.

6. BOUNDARIES OF THE EVIDENCE

The numerical findings establish the answers to finite material-selection questions. They do not establish comparative teaching effectiveness. No class has been recruited for this investigation, and no pretest, post-test, satisfaction score, or learning-effect estimate is available. A subsequent educational evaluation should compare the changing-brief activity with a time-matched fixed-brief activity after equivalent preparation. Assessment should use unfamiliar formulations or requirements so that remembering an identifier cannot substitute for transfer of the decision rule. Marking agreement, prior preparation, completion time, and the distinction between individual and paired work would need explicit treatment.

Physical interpretation also remains limited by the measurements. Distinct recipes do not establish independent batches, and the missing specimen, curing, and loading details prevent an estimate of repeatability. The workability responses do not include every fresh-state property, and strength at one age does not establish durability, structural adequacy, or service performance. A later laboratory activity should document the material sources, batching sequence, curing conditions, specimen geometry, test timing, and replicate structure before using observed variation to select an allowance.

The assigned limits and allowances intentionally make selection boundaries visible. Their instructional usefulness should not be confused with acceptance criteria for construction. Similarly, a mathematically smaller relaxation of a teaching bound is not automatically a permissible practical change. The requirement may encode an obligation that the instructor's simplified exercise does not represent. The strongest defensible statements therefore identify the candidate, the conditions supporting its selection, and the additional evidence required before extending that conclusion.

7. CONCLUSION

Changing specifications turns concrete selection into a conditional reasoning task. The exercise connects simultaneous workability and strength requirements to a minimum-cement objective, then makes the condition invalidating each recommendation explicit. Exact enumeration establishes the nominal choices, the effect of assigned allowances, the undominated cement–margin alternatives, and a brief whose slump and strength requirements are already incompatible within the formulations. The graphical treatment distinguishes physical observation, individual limit clearance, selection regions, successive exclusions, condition intersections, and binder allocation. Learner prompts and their worked answers are integrated with a ninety-minute sequence and an analytic rubric. The calculations support the numerical correctness and instructional availability of these cases. Learning gains, production uncertainty, and construction suitability remain separate questions requiring their own evidence.

Conflict of Interests

The author declares that they have no conflicts of interest.

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Data Availability

The data supporting the findings of this study are available from the author upon reasonable request.

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