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ICAR Mixture Proportioning Procedure for Self-Consolidating Concrete

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ICAR Mixture Proportioning Procedure for Self-Consolidating Concrete

By: Eric P. Koehler and David W. Fowler

ICAR Project 108: Aggregates In Self-Consolidating Concrete

International Center for Aggregates Research
University of Texas at Austin

www.icar.utexas.edu

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1.0 Introduction

Self-consolidating concrete (SCC) is an advanced type of concrete that can flow under its own mass without vibration, pass through intricate geometrical configurations, and resist segregation. The use of SCC can result in increased construction productivity, improved jobsite safety, and improved concrete quality. To achieve SCC workability, the materials and mixture proportions must be carefully selected. The ICAR mixture proportioning procedure was developed as part of ICAR Research Project 108: *Aggregates in Self-Consolidating Concrete*. This research project evaluated the workability and hardened properties of SCC mixtures composed a wide range of materials and mixture proportions.

The ICAR mixture proportioning procedure is based on a fundamental, rheology-based framework for concrete workability and is designed and written to be accessible and comprehensible. The procedure provides specific guidelines for each aspect of the mixture proportioning process but intentionally avoids long calculations or restrictive, discrete inputs. Instead, deliberate laboratory testing is conducted with actual job materials to establish final mixture proportions efficiently. All required testing is conducted with methods standardized by ASTM International.

2.0 Definitions

Aggregate Compacted Voids Content: The volume of voids between fully compacted aggregates (100% - packing density). For purposes of this mixture proportioning procedure, the compacted voids content is determined in accordance with ASTM C 29 (dry-rodded compaction) on the combined aggregate grading. The compacted voids content is calculated as shown in Equation (1):

$$\%voids_{compacted\_agg} = \left(1 - \frac{DRUW}{\left(62.4\,{}^{lb}\!/_{ft^3}\right)\sum_{i=1}^{n}\left(p_i\left(SG_{OD}\right)_i\right)}\right) * 100\% \quad (1)$$

where DRUW is the dry-rodded unit weight of the combined aggregate (lb/ft^3), p_i is the volume of aggregate fraction *i* divided by the total aggregate volume, and $(SG_{OD})_i$ is the oven-dry specific gravity of aggregate fraction *i*.

Angularity: The sharpness of the corners and edges of a particle. (Shape describes a particle on the coarsest scale, angularity an intermediate scale, and texture the finest scale.) For SCC, the angularity characteristics of the aggregates and powder are relevant.

Filling Ability: The ability of concrete to flow under its own mass and completely fill formwork.

Passing Ability: The ability of concrete to flow through confined conditions, such as the narrow openings between reinforcing bars.

Paste Volume: The volume of water, air, and powder.

Plastic Viscosity: The resistance to flow once the yield stress is exceeded. Mixtures with high plastic viscosity are often described as "sticky" or "cohesive". Concrete with higher plastic viscosity takes longer to flow. It is closely related to T_{50} and v-funnel time (higher plastic viscosity → higher T_{50} and v-funnel time). It is computed as the slope of the shear stress versus shear rate plot from rheometer flow curve measurements.

Powder: Solid materials finer than approximately 75 μm (No. 200 sieve) including cement, supplementary cementitious materials (SCMs), and mineral fillers (e.g. finely ground limestone or other minerals and dust-of-fracture aggregate microfines). (There is not a discrete size for distinguishing solid materials that should be included in the paste; however, 75 μm is a reasonable and practical value.)

Rheology: The scientific study of flow. In the context of SCC, rheology refers to the evaluation and manipulation of yield stress, plastic viscosity, and thixotropy to achieve desired levels of filling ability, passing ability, and segregation resistance.

Segregation Resistance: The ability of concrete to remain uniform in terms of composition during placement and until setting. Segregation resistance encompasses both dynamic and static stability.

Stability, Dynamic: The resistance to segregation when external energy is applied to concrete—namely during placement.

Stability, Static: The resistance to segregation when no external energy is applied to concrete—namely from immediately after placement and until setting.

Thixotropy: The reversible, time-dependent decrease in viscosity in a fluid subjected to shearing. For SCC, thixotropy is important for formwork pressure and segregation resistance.

Yield Stress: The amount of stress to initiate (static yield stress) or maintain (dynamic yield stress) flow. It is closely related to slump flow (lower yield stress → higher slump flow). It is calculated as the intercept of the shear stress versus shear rate plot from rheometer flow curve measurements.

Shape: The relative dimensions of a particle. Common descriptors of shape include flatness, elongation, and sphericity. (Shape describes a particle on the coarsest scale, texture the finest scale, and angularity an intermediate scale.) For SCC, the shape characteristics of the aggregates and powder are relevant.

Texture: The roughness of a particle on a scale smaller than that used for shape and angularity. (Shape describes a particle on the coarsest scale, texture the finest scale, and angularity an intermediate scale.) For SCC, the texture characteristics of the aggregates and powder are relevant.

Workability: The empirical description of concrete flow performance. For SCC, workability encompasses filling ability, passing ability, and segregation resistance. Workability is affected by rheology.

3.0 Framework

The ICAR mixture proportioning procedure is based on the representation of SCC as a suspension of aggregates in paste, as depicted schematically in Figure 1. This representation provides a consistent, fundamental framework for evaluating mixture proportions. To proportion SCC, three factors are altered: the aggregates, the paste volume, and the paste composition. The aggregates are first selected based on grading, maximum size, and shape, angularity, and texture. Instead of considering the properties of the fine, intermediate, and coarse aggregates separately, the properties of the combined aggregates are evaluated simultaneously. Next, the paste volume is established for the given aggregates. Paste is defined to consist of water, air, and all solid materials finer than approximately 75 µm including cement, cementitious materials, and mineral fillers. A minimum amount of paste must be provided to achieve SCC properties. The required minimum paste volume depends mainly on the aggregates and is largely independent of the composition of the paste. Lastly, the paste composition—namely the relative amounts of water, powder, and air and the blend of powder—is optimized to achieve the desired concrete rheology and hardened properties. Increasing the paste volume is not necessarily associated with increasing the cement or cementitious materials content.

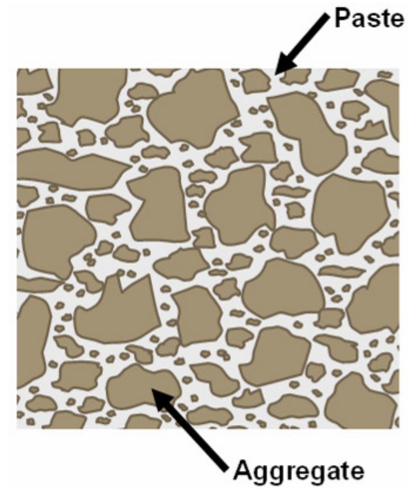


Figure 1: Schematic Representation of Aggregate in Cement Paste

4.0 Criteria for Evaluating SCC

The required workability and hardened properties of SCC mixtures can vary widely depending on the application. Workability should be evaluated in terms of filling ability, passing ability, and segregation resistance. Each of these three workability characteristics should be evaluated independently. The extent to which SCC must exhibit filling ability, passing ability, and segregation resistance should be established based on the application Table 1. Hardened properties should be evaluated in the same manner as for conventionally placed concrete. The relationships between hardened properties and materials and mixture proportions for conventionally placed concrete generally apply to SCC. Certain modifications to mixture proportions needed to ensure workability may affect hardened properties. These modifications may include higher paste volume, increased sand-aggregate ratio, and reduced maximum aggregate size. Conversely, requirements for hardened properties may result in limits on certain parameters important to achieving workability, such as cement content, paste volume, and water-cementitious materials ratio. In many applications, the low water-cementitious materials ratios and use of SCMs required to achieve workability result in hardened properties that significantly

Table 1: Workability Criteria

Property	Application Dependency
Filling Ability	Low. Members with tight spaces—such as with narrow widths or congested reinforcement—and applications where concrete must flow long horizontal distances may require greater filling ability. High placement energy—such as that generated by pumping or by gravity acting on a large mass of concrete—may reduce filling ability requirements.
Passing Ability	High. Applications may range from unreinforced or lightly reinforced sections (no passing ability requirements) to narrow sections containing highly congested reinforcement (strict passing ability requirements).
Segregation Resistance	Low. All mixtures must exhibit segregation resistance. Requirements for dynamic stability may be higher for sections with highly congested reinforcement or applications were concrete is dropped from vertical heights or required to flow long horizontal distances.

exceed design requirements. When possible, care should be taken to not unnecessarily over-design for hardened properties.

The methods to test and achieve workability are described in Table 2. To achieve filling ability, concrete must have adequate paste volume and paste rheology for the given combined aggregate. Sufficient paste volume ensures that voids between aggregates are filled and that sufficient spacing is provided between aggregates. If the concrete contains insufficient paste volume, the paste will not convey the aggregates regardless of the rheology of the paste. In this case, increasing the HRWRA dosage may result in very low paste viscosity and severe bleeding. Paste with very low viscosity will quickly flow out of the aggregates without mobilizing the aggregates. In the slump flow test, the concrete will not achieve the desired slump flow with adequate stability, if it at all. Even with the proper paste volume, concrete must also have proper rheology, which is directly affected by the paste rheology. Proper paste rheology ensures that the paste can convey aggregates uniformly as the concrete flows and that the concrete can fill all corners of the formwork. Concrete that is too viscous may be difficult to pump and place. Low concrete viscosities may result in poor dynamic stability. Harsh concrete mixtures can occur when the paste volume or paste viscosity is too low. In such a case, the concrete does not flow smoothly and may not completely fill all corners of the formwork and produce a smooth top-surface finish. Filling ability should be tested with the slump flow test, including measurements of the time to spread 50 mm (T_{50}) and visual stability index (VSI). The slump flow spread ensures that the yield stress is sufficiently low for the concrete to flow under its own mass. The final adjustment of slump flow should be made by varying the HRWRA dosage. Minimum and maximum limits should be imposed on T_{50}—minimum limits ensure the concrete exhibits adequate stability while maximum limits ensure the concrete is not too difficult to place. The VSI is a quick but approximate indication of the stability of the mixture; however, an acceptable VSI does not ensure adequate stability. In addition, a visual assessment of harshness should be made. When testing concrete in the laboratory or producing it in the field, a constant slump flow should be maintained for all mixtures because slump flow is the main characteristic distinguishing SCC from conventionally placed concrete. The value of the required slump flow depends on the application. With the slump flow constant, the effects of changing proportions on filling ability, passing ability, and segregation resistance can be evaluated. Typically, the range of HRWRA dosages corresponding to the range of slump flows associated with SCC is small.

Table 2: Methods to Test and Achieve SCC Fresh Properties

Property	How to Test		How To Achieve
	Method	Criteria	
Filling Ability	Slump Flow (ASTM C 1611) *Inverted cone orientation recommended.*	Minimum slump flow. Values can range from 22 to 30 inches depending on the degree of filling ability. Values of 24-27 inches appropriate for most applications. The ability to achieve higher slump flows than needed without segregation is a demonstration of robustness. Minimum and maximum T_{50}. Minimum values ensure stability; maximum values ensure placeability. For inverted cone orientation, values of 2-7 s appropriate for most applications. Maximum VSI. Can be used for severe cases of segregation. Values of 1.0 or less acceptable for most applications.	Aggregate: improve shape and angularity to reduce interparticle friction, use finer grading to reduce harshness or coarser grading to reduce viscosity Paste Volume: ensure sufficient minimum paste volume to fill voids between aggregates and reduce interparticle friction between aggregates Paste Composition: ensure viscosity is not too high (sticky) or too low (instability); increase HRWRA dosage to increase slump flow
Passing Ability	J-Ring (ASTM C 1621)	Maximum change in height from inside to outside of ring. Can be as low as no difference. Values of 0.5-1.0 inches acceptable for most moderately reinforced sections. No need to measure for unreinforced or lightly reinforced elements *(Alternate criterion: maximum difference in slump flow with and without j-ring.)* Size and spacing of bars should be constant, vary acceptable change in height or in slump flow based on application.	Aggregate: reduce amount of larger particles by reducing coarseness of grading or maximum aggregate size, improve shape and angularity to reduce interparticle friction Paste Volume: increase paste volume to reduce aggregate volume and interparticle friction between aggregates Paste Composition: reduce paste viscosity or increase HRWRA dosage to increase slump flow
Segregation Resistance	Column Segregation (ASTM C 1610)	Maximum segregation index. A value of 15% is appropriate for most applications but may need to be reduced in some applications. For prequalification of mixtures, tests should be performed the over range of water contents and HRWRA dosages possible during production. Proper sampling is crucial.	Aggregate: Use more uniform grading (avoid gap gradings), reduce coarseness of aggregate grading or maximum aggregate size Paste Volume: increase paste volume Paste Composition: ensure paste viscosity not too high or too low, reduce slump flow (lower HRWRA dosage), optimize workability retention (accelerate loss of slump flow in formwork), use VMA

Passing ability is primarily affected by the aggregate characteristics and the paste volume. Reducing the maximum aggregate size and coarseness of an aggregate grading and improving the aggregate shape and angularity result in increased passing ability. Increasing the paste volume reduces the volume of aggregates and reduces the interparticle friction between aggregates. In addition, reducing the paste yield stress or viscosity improves passing ability. Passing ability should be measured with the j-ring because it provides an independent measurement of passing ability. The j-ring test can be evaluated by measuring either the difference in height between the inside and outside of the ring or the difference in slump flow measured with and without the ring. It is strongly recommended that the difference in height be measured because (1) the difference in slump flow with and without the j-ring is often within the precision of the slump flow test and (2) the difference in slump flow may not reflect the extent of blocking (such as when the thickness of the concrete flowing out of the j-ring is thinner than for the concrete tested without the j-ring—due to differences in blocking—but the spread is approximately the same). The size and spacing of reinforcement bars should remain constant while the maximum value for the change in height should be established for the application.

Segregation resistance encompasses both static and dynamic stability. Static stability is affected by the relative densities of the aggregate and paste, the rheology of the paste with time, the aggregate shape and grading, and the characteristics of the element (such as width and spacing of reinforcement). Changing the paste rheology is generally the most productive means of improving static stability. An SCC mixture with an aggregate that is well-graded for segregation resistance can exhibit severe segregation if the paste rheology is improper. The paste should have sufficiently high yield stress and plastic viscosity and should exhibit sufficient thixotropy. Improving the aggregate grading is also effective for reducing segregation resistance. Dynamic stability is mainly affected by the cohesiveness and passing ability of the concrete. Static stability should be measured with the column segregation test while dynamic stability is usually measured indirectly with measurements of filling and passing ability.

Testing requirements vary between the laboratory and field. To qualifying mixtures in the laboratory, the slump flow, j-ring, and column segregation tests should be used to evaluate filling ability, passing ability, and segregation resistance, respectively. Additionally, the robustness of each of these characteristics should be evaluated by varying the water content and HRWRA dosage over the ranges expected to be encountered in production. In the field, it is often only necessary to perform the slump flow test. The slump flow spread should be used in the field to verify that the HRWRA dosage is correct while T_{50} should be used to evaluate unexpected variations in mixture proportions (most likely water content). The j-ring test does not normally need to be used in the field because passing ability primarily depends on the aggregates and paste volume and to a much lesser extent on paste rheology. As long as the aggregates and paste volume remain reasonably consistent in the field and the slump flow test is used to ensure proper concrete rheology, it is not necessary to measure passing ability in the field. The column segregation test is too time-consuming for use in the field. In performing the column segregation test in the laboratory, representative sampling is crucial. When using the column segregation test to qualify mixtures, it is especially important to test at a range of water contents and HRWRA dosages because (1) segregation resistance is highly dependent on paste rheology and (2) it is possible for the paste rheology to vary substantially due to small variations in HRWRA dosage and water content (such as from variations in aggregate moisture conditions). If tests are conducted in the laboratory with the range of paste rheology expected to be encountered during production—by varying the water content and HRWRA dosage—no further segregation testing is required in the field provided the slump flow test is used to monitor concrete rheology indirectly (with slump flow and T_{50}).

Rheology can be used to characterize concrete flow characteristics and to optimize mixtures for filling ability, passing ability, and segregation resistance. Rheology involves measuring yield stress, plastic viscosity, and thixotropy. Yield stress describes the stress to initiate (static yield stress) or maintain (dynamic yield stress) flow. The yield stress should be near zero to ensure concrete flows under it own mass. Plastic viscosity describes the resistance to flow once the yield stress is exceeded. Mixtures with high plastic viscosity appear sticky and cohesive. Plastic viscosity should not be too low, which would result in instability, or too high, which would result in mixtures that are difficult to pump and place. Thixotropy describes the reversible, time-dependent reduction in viscosity in a concrete subjected to deformation (shearing). Thixotropy is caused by the build-up of a structure in fresh concrete at rest. This structure, which provides an initial resistance to deformation, is destroyed upon application of sufficient deformation to the concrete. Thixotropy, which is manifested in the difference between static and dynamic yield stress or the breakdown area between upward and downward rheometer flow curves, contributes to increased segregation resistance and reduced formwork pressures. Too much thixotropy; however, reduces placeability.

Concrete rheology is a function of the aggregates, paste volume, and paste rheology. Angular and poorly shaped aggregates increase yield stress and plastic viscosity. Increasing the paste volume reduces yield stress and plastic viscosity. If the aggregates and paste volume are held constant, changes in paste rheology are generally matched in concrete rheology (e.g. increasing paste yield stress and viscosity increases concrete yield stress and viscosity). To increase filling ability and passing ability, the yield stress and plastic viscosity should be reduced. If the yield stress and plastic viscosity are too low; however, the concrete may become unstable, resulting in reduced filling and passing abilities. To increase segregation resistance, the yield stress and plastic viscosity should generally be increased.

Rheology is normally measured with a rheometer; however, certain empirical tests are correlated with rheological parameters. Specifically, reductions in yield stress generally result in higher slump flows while increases in plastic viscosity generally result in higher T_{50} and v-funnel flow times. Even if rheology parameters are not measured with a rheometer, considering workability in terms of rheology is often useful.

5.0 Methodology

The ICAR SCC mixture proportioning procedure consists of three steps: select aggregates, select paste volume, and select paste composition. The procedure is conducted in this order because paste volume depends primarily on the aggregate characteristics and paste composition depends on the aggregate characteristics and paste volume. The role of each factor is summarized in Table 3 and the specific tasks for each step are listed in Table 4. Table 5 indicates how changes in mixture proportions affect specific aspects of SCC workability.

Table 3: Role of Factors to Control in Mixture Proportioning

Factor	Objective	Sub-Factors	Target	Typical Values
Aggregates	Minimize voids content (increase packing density) and reduce interparticle friction; limit grading as needed for passing ability and segregation resistance	Maximum Size	Reduce for passing ability or segregation resistance	¾ or 1 inch for most applications; reduce to as low as 3/8 inch for challenging passing ability
		Grading	None universally optimal, best depends on aggregate and application	Uniform gradings with high packing density preferred, 0.45 power curve or finer, S/A=0.40-0.50
		Shape, Angularity, Texture	Reduce interparticle friction	Equidimensional, rounded aggregates preferred but any can be accommodated
Paste Volume	Ensure filling and passing ability by filling voids in compacted aggregates and separating aggregates (lubrication), provide additional paste for robustness	Filling Ability	Fill voids and lubricate aggregates	Total paste volume = 28-40%
		Passing Ability	Reduce aggregate volume and interparticle friction	
		Robustness	Minimize effects of changes in materials and proportions	
Paste Composition	Ensure adequate concrete rheology (yield stress, plastic viscosity, thixotropy) and hardened properties (strength, stiffness, durability), optimize economy	Water	w/p for rheology, w/c for early-age hardened properties, w/cm for long-term hardened properties	w/p = 0.30-0.45, may be higher with VMA
		Powder	Relative amounts of cement, SCMs, and mineral fillers for economy, strength, durability, and to fill paste volume	Fly ash, slag, silica fume, ground limestone filler, dust-of-fracture aggregate microfines
		Air	As needed for durability	Same requirements as for conventionally placed concrete
Adjust HRWRA dosage to reach desired slump flow (yield stress for self-flow)				

Table 4: Summary of ICAR SCC Mixture Proportioning Procedure

STEP 1:
Aggregates
	1. Select individual aggregate sources (fine, intermediate, coarse sizes)
	2. Evaluate various aggregate blends.
	   a. Maximum aggregate size
	   b. Grading (0.45 power curve, percent retained on each sieve)
	   c. Shape and angularity (visually rate on scale of 1 to 5)
	3. Determine compacted voids content of each blend.

STEP 2:
Paste Volume
	1. Determine minimum paste volume for filling and passing ability. Select the larger.
	   a. Paste volume for filling ability (Calculate from compacted voids content and visual rating of shape and angularity. Confirm with tests with various paste volumes and constant paste composition. Concrete should be able to achieve target slump flow without bleeding or segregation.)
	   b. Paste volume for passing ability (Establish with tests with various paste volumes and constant paste composition.)
	2. Add paste volume for robustness.

STEP 3: Paste Composition	1. Select cement, SCMs, and mineral fillers. 2. Select maximum w/c and w/cm and maximum and minimum SCM rates for early-age and long-term hardened properties. If mineral fillers affect hardened properties, specify maximum and minimum rates. 3. Select air content for durability (assume 2% if not air entrained). 4. Select w/p (typically 0.30-0.45, may be higher with VMA) and powder blend (subject to limits on hardened properties) for workability. 5. Calculate paste composition. 6. Evaluate trial mixtures and adjust paste composition based on Table 5.

Table 5: Effects of Mixture Proportions on SCC Workability

		Slump Flow	**Viscosity**	**Filling Ability**	**Passing Ability**	**Segregation Resistance**
Aggregates	⬆ Maximum Size	⬆	⬇	⬆⬇	⬇	⬇
	Grading	Higher pkg. density; coarser or gap grading: ⬆	Higher pkg. density or gap grading: ⬇	⬆⬇	Finer grading: ⬆	Uniform or finer grading: ⬆
	Improved Shape	⬆	⬇	⬆	⬆	⬇
	Increased Angularity	⬇	⬆	⬇	⬇	⬆
⬆ Paste Volume		⬆	⬇	⬆	⬆	⬆
Paste Composition	⬆ Water/Powder	⬆	⬇	⬆	⬆	Not too high or too low: ⬆
	Fly Ash	⬆	⬇	⬆	⬆	⬆⬇
	Slag	⬆⬇	⬆⬇	⬆⬇	⬆⬇	⬆⬇
	Silica Fume (Low %)	⬆⬇	⬇	⬆	⬆	⬆⬇
	Silica Fume (High %)	⬇	⬆	⬆⬇	⬇	⬆⬇
	VMA	⬇	⬆	⬆	⬆⬇	⬆
	HRWRA	⬆	⬇	⬆	⬆	⬇
	Air	⬆⬇	⬇	⬆	⬆	⬆⬇

Notes:
1. There are exceptions for every case.
2. Slump flow is inversely proportional to yield stress. Viscosity is proportional to T_{50} or v-funnel time.
3. This table reflects trends over the range of values typical for SCC and may not apply for extreme values. For instance, increasing water/powder to extremely high values will not improve filling or passing abilities. Stated effects assume mixtures are adjusted to achieve SCC slump flow before and after change.

5.1 Selection of Aggregates

Aggregates should be selected to maximize aggregate content for the given application because aggregates are the lowest-cost component aside from water and higher aggregate contents are often associated with improved hardened properties. The three sub-factors for selecting aggregate characteristics are maximum size, grading, and shape, angularity, and texture. Additionally, certain clays present in aggregates may increase HRWRA demand for a given slump flow. Both grading and shape, angularity, and texture are important: consideration of one at the exclusion of the other is inappropriate. The properties of the combined aggregates should be considered.

Maximum Size. The maximum aggregate size should usually be selected as large as possible provided the workability requirements can be achieved. Larger maximum aggregate sizes are beneficial for workability to the extent that they increase the range of aggregate sizes and result in improved grading. The maximum aggregate size can be reduced to increase passing ability and segregation resistance. A maximum aggregate size of ¾ or 1 inch is acceptable for most applications. The maximum aggregate size may be reduced to as low as 3/8 inch to ensure passing ability.

Grading. There is not a universally optimal grading for SCC. The best grading depends on the application and the aggregate. For example, a grading with a large fraction of coarse particles may reduce HRWRA demand and plastic viscosity but result in poor passing ability. Further, the net effect of adding a poorly shaped aggregate to improve grading may be adverse. In general, uniformly graded aggregate—namely without a deficiency or excessive amount of material on any two consecutive sieves (Figure 2)—and gradings with high packing densities are favorable. Gap gradings often result in lower concrete HRWRA demand and plastic viscosity; however, they should normally be avoided because they result in increased segregation. In many cases, the 0.45 power curve is a favorable grading because it provides high packing density and is associated with low concrete HRWRA demand and plastic viscosity. The 0.45 power curve is developed on a plot of percent passing versus size, where the sizes are raised to the 0.45 power. A straight line is normally drawn from the origin to the maximum aggregate size, as shown in Figure 2. This approach; however, results in a large volume of material passing the No. 200 sieve, which should more appropriately be considered powder and accounted for as part of the paste. Therefore, in constructing the 0.45 power curve, the straight line should be drawn between the No. 200 sieve and the maximum aggregate size. Gradings finer than the 0.45 power curve are also usually preferred to coarser gradings because they reduce harshness. As a first approach when combining two aggregates, the sand-aggregate ratio should be set between 0.40 and 0.50. It is often favorable to blend three or more aggregates in cases where combining fewer aggregates would result in a gap grading. Because smaller aggregate sizes are commonly used for SCC (e.g. ¾ or 1 inch), problems with gap gradings may not be as severe as if larger maximum aggregate sizes were used (e.g. 1.5 inches).

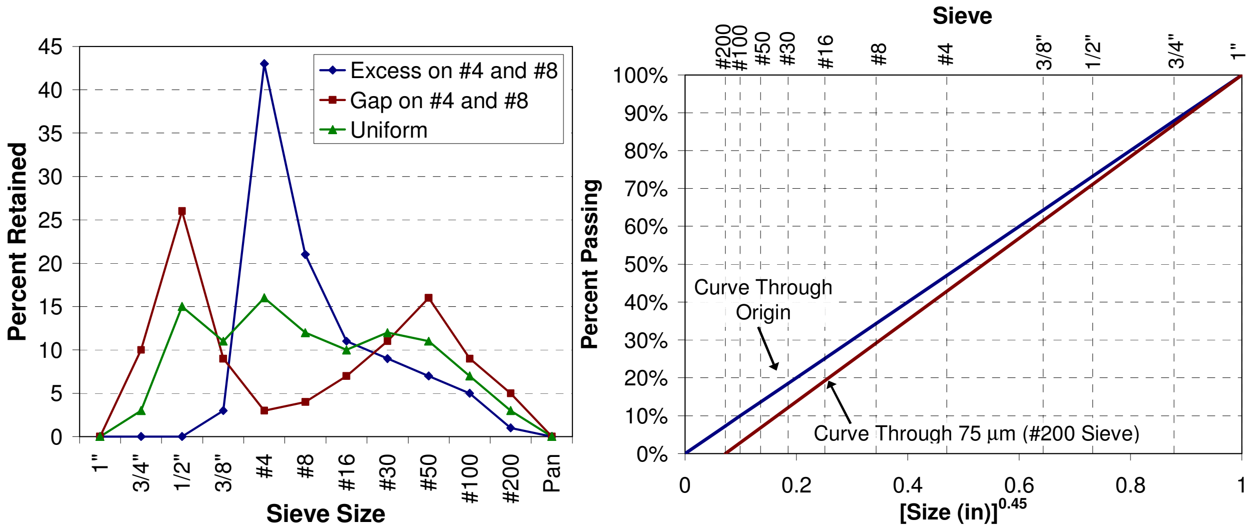
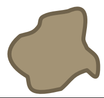
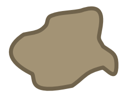
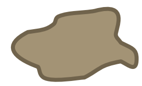
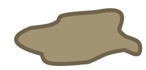
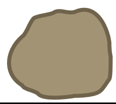
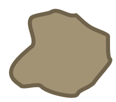
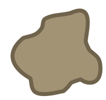
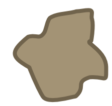
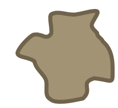


Figure 2: Example Percent Retained Plots and 0.45 Power Curve Plot

Shape, Angularity, and Texture. The shape and angularity of aggregates can significantly affect workability by influencing the aggregate compacted voids content and the interparticle friction between aggregates. Equidimensional, well-rounded aggregates are best for workability; however, aggregates of all shape and angularity can be accommodated in SCC by increasing the paste volume. Once the paste volume is sufficient for a given aggregate, concrete workability can be further enhanced by adjusting the paste composition. Texture has minimal effect on workability. A visual examination is typically sufficient for characterizing aggregate shape and angularity. Table 6 should be used to assign a single visual rating, on a scale of 1 to 5, representing both shape and angularity. (An aggregate source may have good shape but poor angularity or vice versa. A single rating representing both shape and angularity should be assigned). A single rating should be assigned to each combined grading. For instance, a crushed coarse aggregate with a rating of 5 blended with a well-shaped natural sand with a rating of 1 would receive a rating of 3 for the combined grading. When possible, historic data on the performance of a particular aggregate in SCC is the best guide for assigning the visual shape and angularity rating.

To select aggregates, various aggregate sources should be considered (fine, intermediate, and coarse sizes). Various blends of the aggregates should be evaluated in terms of maximum aggregate size, grading, and shape and angularity. The compacted voids content and visual shape and angularity rating should be determined on all aggregate blends. Measuring the compacted voids content on a series of aggregate blends—such as for a range of S/A values—can be used to identify the minimum voids content. The minimum voids content (maximum packing density) may not be optimal in all cases because other considerations—such as passing ability, segregation resistance, or harshness—may be more important.

Table 6: Guidelines for Assigning Visual Shape and Angularity Rating

	Visual Shape and Angularity Rating (R_{S-A})				
	Well-Shaped, Well Rounded ←				→ Poorly Shaped, Highly Angular
	1	**2**	**3**	**4**	**5**
Shape	most particles near equidimensional 	modest deviation from equidimensional 	most particles not equidimensional but also not flat or elongated 	some flat and/or elongated particles 	few particles equidimensional; abundance of flat and/or elongated particles 
Angularity	well-rounded 	rounded 	sub-angular or sub-rounded 	angular 	highly angular 
Examples	most river/glacial gravels and sands	partially crushed river/glacial gravels or some very well-shaped manufactured sands	well-shaped crushed coarse aggregate or manufactured sand with most corners > 90°	crushed coarse aggregate or manufactured sand with some corners ≤90°	crushed coarse aggregate or manufactured sand with many corners ≤90° and large convex areas

5.2 Selection of Paste Volume

A minimum paste volume must be provided to ensure filling ability and passing ability. Without the minimum paste volume, SCC workability properties cannot be achieved, regardless of the composition of the paste (e.g. power content, w/p, use of VMA, etc.). The minimum required paste volume should be determined separately for filling ability and passing ability. Additional paste volume in excess of the minimum required for filling or passing ability increases robustness.

The minimum paste volume for filling ability is depicted conceptually in Figure 3. Concrete without the minimum paste volume for filling ability may not achieve the desired slump flow regardless of the HRWRA dosage, may be highly viscous, may exhibit severe bleeding and segregation, and may appear harsh. A certain amount of paste must be provided to fill the voids between compacted aggregates. If only this amount of paste were provided, the concrete would not flow due to the significant interparticle friction between aggregates. Therefore, additional paste must be provided to separate aggregates. This paste used to separate the aggregates provides lubrication by reducing interparticle friction between aggregates.

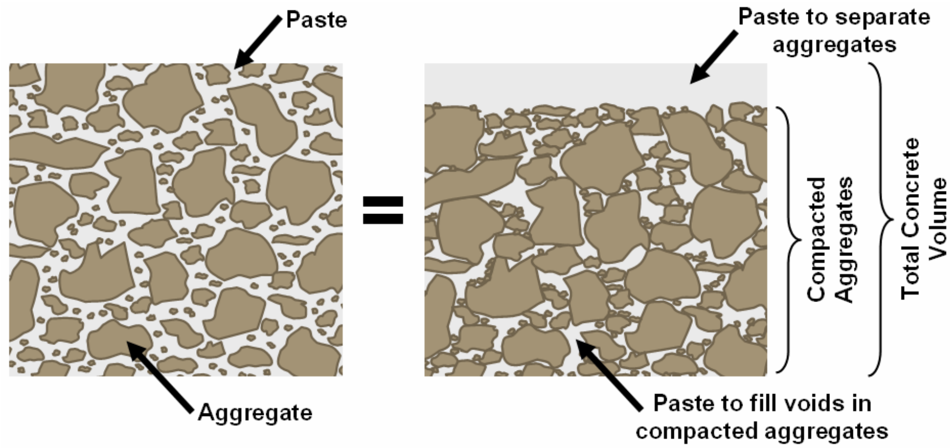


Figure 3: Schematic Representation of Aggregate in Cement Paste

The total amount of paste for filling ability ($V_{paste\text{-}filling\_ability}$) is the sum of the paste to fill the voids ($V_{paste\text{-}voids}$) and to provide spacing between aggregates ($V_{paste\text{-}spacing}$), as expressed in Equation 2

$$V_{paste-filling\_ability} = V_{paste-voids} + V_{paste-spacing} \tag{2}$$

The minimum amount of paste needed to provide spacing between aggregates depends primarily on the shape and angularity of the combined aggregate and ranges from 8% for equidimensional, well-rounded aggregates (visual shape and angularity rating of 1) to 16% for poorly shaped, angular aggregates (visual shape and angularity rating of 5). (Aggregates with extremely poor shape and angularity characteristics may require even more than 16%.) The minimum paste volume for filling ability is largely independent of the paste composition—provided the paste composition is within the range of typical SCC mixtures. The total paste volume for filling ability (expressed as a percentage of concrete volume) can be calculated as a function of the paste volume for spacing (expressed as a percentage of concrete volume) and the percentage of voids in the compacted aggregate ($\%voids_{compacted\_agg}$, expressed as a percentage of the bulk aggregate volume), as shown in Equation (3)**Error! Reference source not found.**:

$$V_{paste-filling\_ability} = 100 - \frac{(100 - V_{paste-spacing})(100 - \%voids_{compacted\_agg})}{100} \tag{3}$$

The amount of spacing paste can be calculated from the visual shape and angularity rating ($R_{S\text{-}A}$), as indicated in Equation (4):

$$V_{paste-spacing} = 8 + \left(\frac{16-8}{4}\right)\left(R_{S-A} - 1\right) \tag{4}$$

Equation (3) indicates that the paste volume for filling ability can be reduced by reducing the compacted aggregate voids content (by increasing the maximum aggregate size, improving the grading, improving the shape and angularity) or by improving the shape and angularity to reduce the volume of spacing paste. It is recommended that tests with various paste volume be conducted to confirm the calculated minimum paste volume. For instance, if a minimum paste volume of 32% is calculated with Equation (3), trial batches should be measured at 30, 32, and 34% to determine the minimum sufficient paste volume (not necessarily the optimal workability because proper paste composition must be established also). Because the minimum paste volume for filling ability is largely independent of the paste composition, the paste composition should be near that expected in the final mixture and should be held constant as the paste volume is varied.

For passing ability, sufficient paste volume is needed to reduce the volume of coarse aggregates and to reduce interparticle friction between aggregate particles. The amount of paste depends mainly on the aggregates (higher maximum sizes and coarser gradings increase the amount of large particles that must pass, reducing passing ability; angular and poorly shaped aggregates increase interparticle friction between aggregates, reducing passing ability) and the paste volume (higher paste volumes decrease the volume of aggregate that must pass and reduce interparticle friction between aggregates, increasing passing ability). The amount of paste needed depends to a lesser extent on the rheology of the paste (lower paste viscosity and higher slump flow result in increased passing ability). To determine the amount of paste needed for passing ability, it is recommended that testing be conducted with the j-ring at various paste volumes with constant paste composition (the paste composition should be near that expected in the final mixture). The determination of minimum paste volume for passing ability for unreinforced or lightly reinforced sections is unnecessary.

If the minimum paste volume for passing ability is higher than that for filling ability, it may be beneficial to modify the aggregate grading by decreasing the maximum aggregate size or decreasing the coarseness of the grading (e.g. higher S/A). This change would reduce the overall minimum paste volume needed by decreasing the minimum paste volume for passing ability, even though the minimum paste volume for filling ability would likely be increased.

The larger of the paste volumes required for filling or passing ability should be selected. Additional paste can be used to increase robustness. The amount of paste needed for robustness depends on the level of quality control and expected variations in materials.

5.3 Selection of Paste Composition

With the paste volume determined, the composition of the paste is selected to achieve the required workability and hardened properties. Selecting the paste composition involves selecting the relative amounts of water, powder, and air and the blend of powder (Table 7). The paste composition is the stage where the distinction between powder-type and VMA-type SCC is made (Table 8). Powder-type SCC consists of high powder contents—with a large portion of the powder content comprised of SCMs and fillers—and a low water-powder ratio. VMA-type SCC utilizes lower powder contents and higher water-powder ratios and, therefore, must incorporate a VMA to ensure stability. The minimum paste volume for filling ability is the same for powder-type and VMA-type SCC.

Table 7: Selection of Paste Composition

	Parameter	Purpose
Water	Water/Cement	Early-age hardened properties
	Water/Cementitious Materials	Long-term hardened properties
	Water/Powder	Workability
Powder	Cement	Strength and durability
	SCMs	Improve workability and durability, reduce heat, reduce cost
	Mineral Fillers	Improve workability, reduce cost, reduce heat
Air	Air Content	Durability

Water Content. The water content is established by selecting limits on water/cement (early-age hardened properties), water/cementitious materials (long-term hardened properties), and water/powder (workability). The high degree of powder dispersion achieved with high dosages of HRWRA may increase the w/c or w/cm needed for a given strength level compared to conventionally placed concrete with no or low dosages of HRWRA. If the powder consists only of cement and SCMs, the w/p is equal to the w/cm. The total water content per unit volume of concrete (e.g. lb/yd^3) is usually similar to that in conventionally placed concrete. The w/p typically varies from 0.30 to 0.45. Higher values of w/p can be used; however, a VMA is typically required. Increasing the w/p decreases the HRWRA demand for a constant slump flow and reduces plastic viscosity. As the paste volume is increased for a given aggregate, the paste viscosity should be reduced. As a first approximation, the total water content per unit volume of concrete should be held constant as the paste volume is increased.

Powder Blend. Given the high powder contents required to achieve SCC workability, it is often necessary to include SCMs or mineral fillers as part of the powder. The powder content must contain a minimum amount of cement for strength and durability. SCMs can be used to improve workability and durability, reduce heat of hydration, and reduce cost. Mineral fillers significantly finer than cement typically enhance workability and may contribute to accelerated strength gain. Mineral fillers approximately the same size of cement typically have minimal effects on workability and do not contribute to strength.

Air Content. Air content requirements for SCC—namely total air content, bubble size, and bubble spacing—are similar to those for conventionally placed concrete.

To select the paste composition, limits on some of the factors listed in Table 7 can be used to compute the relative amounts of water, powder, and air. Typical ranges of values for powder content and water-powder ratio are given in Table 8. This table should be used as a general guideline only; trial batches of concrete should be used to establish final proportions. Table 5 describes how to adjust paste composition to achieve desired workability properties. In achieving the correct workability, the paste composition should be adjusted to reach the proper slump flow and viscosity. Slump flow is adjusted by varying the HRWRA dosage. The HRWRA demand for a given slump flow can be reduced by varying the paste composition, paste volume, and aggregates. The viscosity determines the ease with which the concrete can be placed and should not be too low (poor stability) or too high (sticky and cohesive). Tests can be conducted on paste or mortar to evaluate the relative effects of various constituents; however, the final paste composition should be established in concrete mixtures because (1) the required paste composition depends on the aggregate characteristics and paste volume and (2) paste tested separately from concrete behaves different than the same paste in concrete. Examples of paste composition calculations are shown in Table 9. Tests for filling ability, passing ability, and segregation resistance should be performed prior to selecting final mixture proportions, if not on every trial batch.

Workability retention should be considered in establishing the paste composition. Factors affecting workability retention are shown in Table 10.

Table 8: Typical Paste Compositions

	Powder-Type	VMA-Type
Powder Content	650-900 lb/yd^3	<650 lb/yd^3
Water/Powder	0.30-0.45	>0.45
Admixture	HRWRA only	HRWRA and VMA
Note: These values are given as a general guideline as there is not a discrete distinction between powder- and VMA-type SCC. Mixtures near the transition between powder and VMA-type may incorporate aspects of each type (e.g. combination type)		

Table 9: Sample Calculations for Paste Composition

Case	Specified Parameters	Parameters							Proportions (lb/yd^3)					
		Paste Volume	w/p	w/cm	w/c	Fly Ash	Mineral Filler	Air	Water	Cement	Mineral Filler	Fly Ash	Coarse	Fine
1	w/cm≤0.60	32%	0.40	0.40	0.40	0%	0%	2%	281.8	704.5	--	0.0	1489.4	1489.4
2	w/cm≤0.60	32%	0.37	0.37	0.529	30%	0%	2%	260.7	493.1	--	211.6	1489.4	1489.4
3	w/cm≤0.60	32%	0.40	0.60	0.60	0%	33.3%	2%	269.4	449.0	224.5	--	1489.4	1489.4
4	w/cm≤0.40, w/c≤0.50	32%	0.40	0.40	0.50	20%	0%	2%	274.2	548.4	--	137.1	1489.4	1489.4
5	w/cm≤0.40, w/c≤0.50	36%	0.325	0325	0.50	35%	0%	2%	274.9	549.8	--	296.1	1401.8	1401.8
6	w/cm≤0.40, w/c≤0.50 6% air	32%	0.40	0.40	0.50	20%	0%	6%	237.6	475.3	--	118.8	1489.4	1489.4

Case 1: Hardened properties do not control. The maximum w/cm is set for 0.60; however, the w/p must be lower to ensure workability. Since cement is the only powder, w/p=w/c=w/cm.
Case 2: The same requirement as case 1, but 30% fly ash is used for economy. The w/p ratio is reduced to offset the reduction in viscosity due to fly ash. Since all powders are cementitious, w/p=w/cm
Case 3: The same requirements as case 1, but mineral filler (microfines) is used, resulting in the specified w/cm.
Case 4: The maximum w/cm is set for long-term properties and w/c is limited to ensure sufficient early-age strength. The fly ash content is maximized while maintaining the specified w/cm and w/c.
Case 5: The same requirements as case 4, but passing ability requirements dictate a higher minimum paste volume. The paste volume is increased by adding fly ash, resulting in a lower w/p and w/cm. The viscosity is approximately unchanged because the increased paste volume and fly ash content reduce viscosity, while the lower w/p increases viscosity.
Case 6: The same requirements as case 4 but with 6% air.

Table 10: Factors Affecting Workability Retention

Factor	Role in Workability Retention
HRWRA type and dosage	Polycarboxylate-based HRWRA admixtures can be designed for various amounts of workability retention. Increasing the dosage increases workability retention.
Retarder type and dosage	Retarders may increase, decrease, or have no effect on workability retention, depending on the chemical composition of the retarder. Increasing the dosage generally increases the effect of the retarder.
Cement, filler, and SCM types and amounts	The physical and chemical properties of the powder constituents affect workability retention.
Concrete rheology	Mixtures that are more viscous tend to have longer workability retention.
Other (weather, agitation)	Hot and dry conditions accelerate the loss of workability. Agitation may increase or decrease workability retention.

6.0 Optimization of Mixtures

Mixtures should be optimized to achieve desired filling ability, passing ability, segregation resistance, hardened properties, economy, and robustness. The optimization of mixtures is often an iterative process, as indicated in Table 11. For instance, if the paste volume is too high, resulting in poor economy and reduced hardened properties, the aggregates can be improved. When the paste volume and aggregates are changed, it may be necessary to adjust the paste composition to achieve proper workability. Table 5 provides specific guidelines for adjusting mixture proportions to achieve SCC workability.

Table 11: Optimization of Mixtures

Step	Tasks	Adjustments
STEP 1 Aggregates	Evaluate various aggregates and gradings, determine voids between compacted aggregates	Paste volume too high? Adjust aggregates.
STEP 2 Paste Volume	Evaluate passing ability and filling ability for range of paste volumes, maintain constant paste composition	Aggregates Changed? Adjust pate volume. Poor robustness? Increase paste volume.
STEP 3 Paste Composition	With paste volume and aggregates set, vary paste composition for workability and hardened properties	Paste volume or aggregates changed? Adjust paste composition.

7.0 Examples

The following examples illustrate the ICAR SCC mixture proportioning procedure.

7.1 Example 1: Precast, Prestressed Concrete

Requirements

A SCC mixture is needed for precast, prestressed beams. The 16-hour release strength must be 5,000 psi based on a specified temperature history; the 28-day strength is specified as 9,000 psi. For filling ability, the specified slump flow is 26-28 inches with a T_{50} between 3 and 7 seconds and a VSI of less than 1.0. For filling ability, the j-ring change in height from inside to outside of the ring is specified as less than 0.50 inches due to the highly congested strands and bars. For segregation resistance, the segregation index from the column segregation test is specified as less than 15%. No air entrainment is required.

Step 1: Aggregates

Two coarse aggregates (3/4" maximum aggregate size) are to be considered: a well-shaped river gravel (specific gravity = 2.59) and crushed limestone coarse aggregate (specific gravity = 2.59). A well-shaped natural sand is used with both aggregates (specific gravity = 2.58). The aggregates are considered at S/A values of 0.40 to 0.50. The visual shape and angularity index is determined to be 1.0 for the river gravel-natural sand blend and 3.0 for the crushed limestone-natural sand blend. The aggregate gradings, shown in Figure 4, are considered acceptable for SCC.

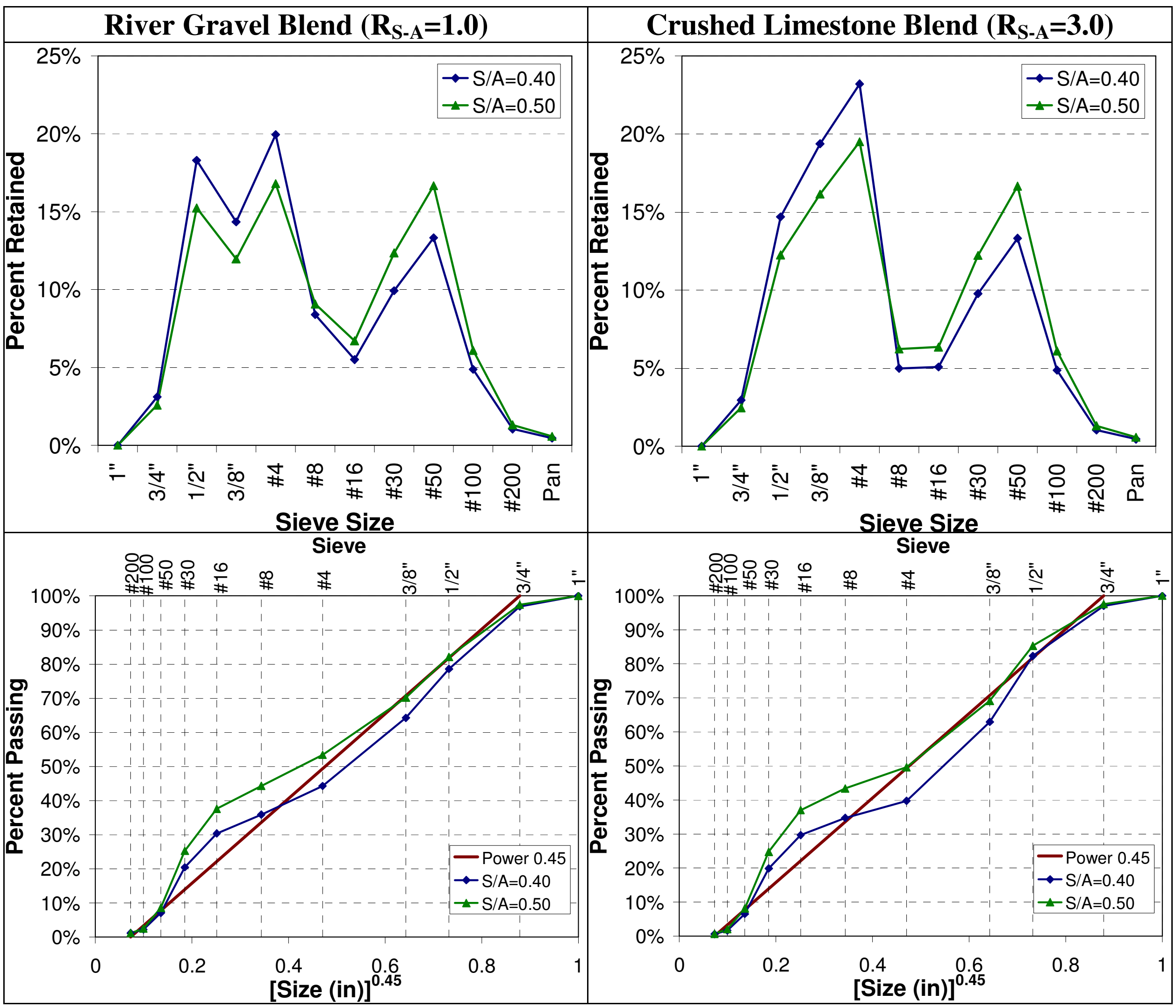


Figure 4: Example 1 Gradings

Step 2: Paste Volume

The paste volume is computed for filling ability based on Equation (3) for each aggregate, as indicate in Table 12. Passing ability is evaluated by varying the paste volume with constant paste composition and evaluating j-ring results. As indicated in Figure 5, the paste volume for passing ability is reduced with reduced coarse aggregate volume (higher S/A) and improved shape and angularity (river gravel versus crushed limestone). Due to the highly congested reinforcement, passing ability requirements control the selection of minimum paste volume. Additional paste volume of 1% is added to each blend for robustness.

Table 12: Example 1 Required Paste Volumes

S/A	River Gravel			Crushed Limestone		
	Voids Content	Req'd Paste Volume		Voids Content	Req'd Paste Volume	
		Filling	Passing		Filling	Passing
0.40	23.9	30	36	23.9	33	41
0.50	23.2	29	32	22.7	32	36

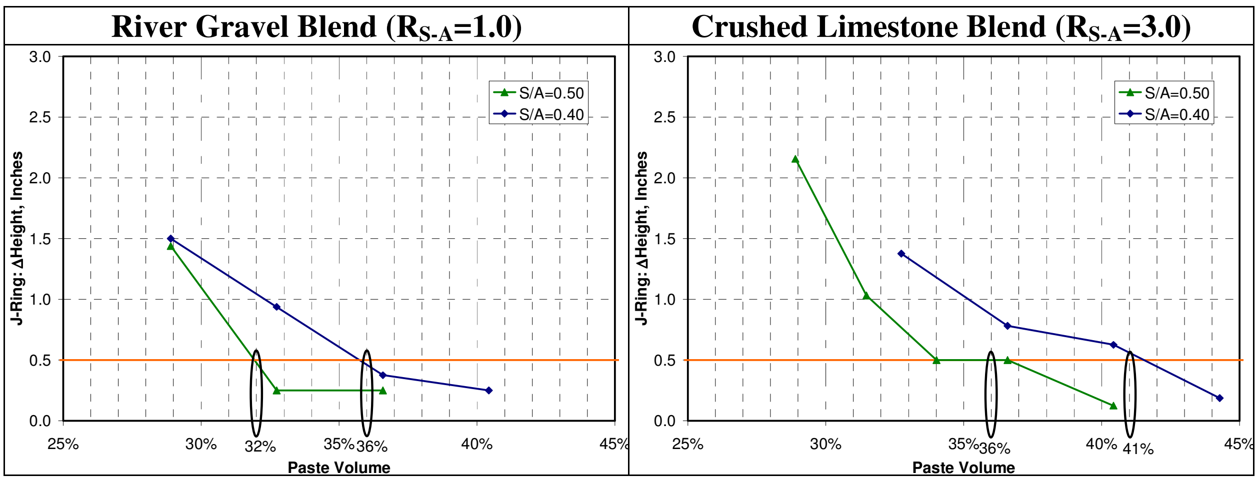


Figure 5: Example 1 Minimum Paste Volume for Passing Ability

Step 3: Paste Composition

A Type III cement (specific gravity = 3.15) and Class F fly ash (specific gravity = 2.33) are selected to comprise the powder. To achieve the required 16-hour compressive strength, the w/c must be 0.41 for the river gravel and 0.45 for the crushed limestone. Fly ash is used to improve workability, reduce heat of hydration, improve durability, and improve economy. The final mixture proportions for each blend are shown in Table 13, based on the results of trial concrete batches. The w/p is set for workability. Increasing the paste volume or fly ash rate for a given aggregate requires a lower w/p for the same approximate workability. Because all powder is cementitious, the w/cm is equal to the w/p. In this example, the microfines content is low and can be neglected in computing the w/p and paste volume. The w/cm is more than adequate to achieve the 28-day compressive strength requirement of 9,000 psi.

Table 13: Example 1 Paste Composition

Mixture	Parameters						Proportions (lb/yd^3)				
	Paste Volume	w/p	w/cm	w/c	Fly Ash	Air	Water	Cement	Fly Ash	Coarse	Fine
River Gravel, S/A=0.40	37%	0.28	0.28	0.412	32%	2%	260.8	633.3	298.0	1649.5	1095.4
River Gravel, S/A=0.50	33%	0.33	0.33	0.413	20%	2%	257.3	623.8	156.0	1461.8	1456.2
Limestone, S/A=0.40	42%	0.27	0.27	0.45	40%	2%	287.8	639.6	426.4	1518.5	1008.5
Limestone, S/A=0.50	36%	0.30	0.30	0.448	33%	2%	270.4	603.8	297.4	1374.5	1369.2

7.2 Example 2: Ready Mixed Concrete

Requirements

A SCC mixture is required for use in a lightly reinforced slab on grade. The specifications require a maximum w/cm of 0.50 and 5% entrained air content. Because the concrete may need to flow long horizontal distances, the slump flow is set to 26-28 inches with a T_{50} of 3-6 s and a VSI ≤ 1.0. A maximum segregation index for the column segregation test is specified as 15%.

Step 1: Aggregates

A rounded, well-shaped fine aggregate (specific gravity = 2.60) and a crushed limestone coarse aggregate with a ¾" maximum aggregate size (specific gravity = 2.60) are selected. The visual shape and angularity index is determined to be 3.0. After considering blends of these two aggregates at S/A values of 0.40 to 0.50, the blend with an S/A of 0.50 is selected because it results in the minimum compacted voids content of 23.9%. The higher S/A results in more of the well-shaped sand and less of the angular, poorly shaped coarse aggregate, which allows lower paste volume and improved workability. The resulting grading, shown in Figure 6, is reasonably uniform and is finer than the 0.45 power curve.

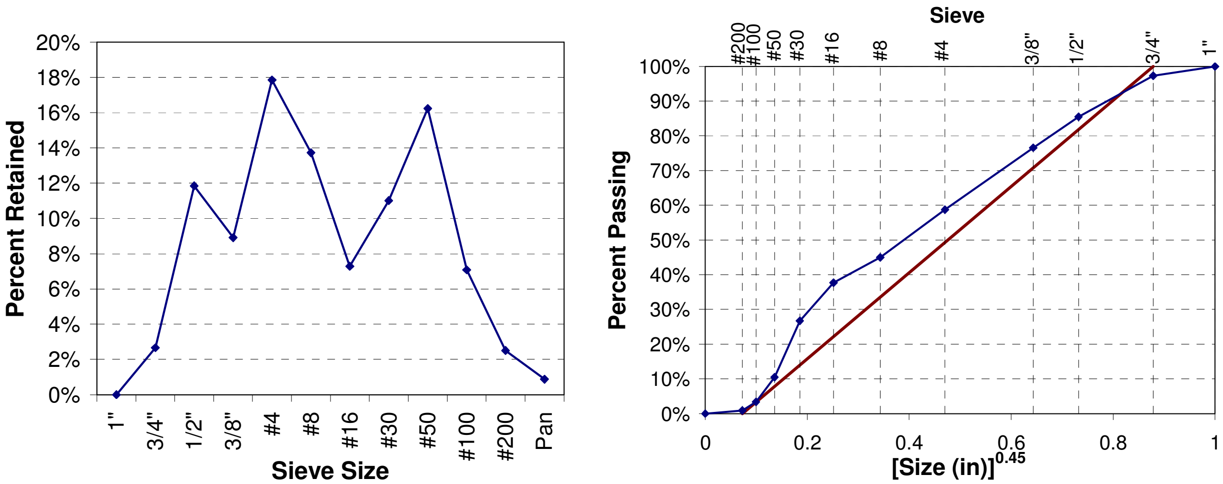


Figure 6: Example 2 Aggregate Grading

Step 2: Paste Volume

The volume of spacing paste and total paste are computed in Equations (5) and (6).

$$V_{paste-spacing} = 8 + \left(\frac{16-8}{4}\right)\left(R_{S-A} - 1\right) = 8 + \left(\frac{16-8}{4}\right)\left(3-1\right) = 12 \quad (5)$$

$$\begin{aligned} V_{paste-filling\_ability} &= 100 - \frac{(100 - V_{paste-spacing})(100 - \%voids_{compacted\_agg})}{100} \\ &= 100 - \frac{(100-12)(100-23.9)}{100} = 33.0 \end{aligned} \quad (6)$$

Because the concrete is to be used in a lightly reinforced slab, it is unnecessary to check passing ability requirements. Concrete mixtures are evaluated at paste volumes of 31, 33, and 35% to confirm the minimum required paste volume. The mixture with 31% paste volume is viscous and exhibits severe bleeding, suggesting inadequate paste volume for filling ability. The mixture with 33%, however, has adequate paste volume. The 33% paste volume required for filling ability is increased by 2% to 35% to assure robustness.

Step 3: Paste Composition

A Type I cement (specific gravity = 3.15) and Class F fly ash (specific gravity = 2.40) are selected to comprise the powder. Trial mixtures are evaluated by varying the fly ash rate and w/p, as shown in Table 14. The fly ash is used at a rate of 35% of the powder mass to improve economy and workability while the w/p is set at 0.36 to establish the target workability. In this example, the microfines content is low and can be neglected in computing the w/p and paste volume.

Table 14: Example 2 Paste Composition

	Parameters						Proportions (lb/yd^3)					Comments
Trial	Paste Volume	w/p	w/cm	w/c	Fly Ash	Air	Water	Cement	Fly Ash	Coarse	Fine	
1	35%	0.40	0.40	0.40	0	5%	281.8	704.5	0.0	1423.7	1423.7	Uneconomical (cement too high)
2	35%	0.40	0.40	0.615	35%	5%	268.8	436.9	235.1	1423.7	1423.7	Viscosity too low (T_{50}= 1.2s), should reduce w/p
3	35%	0.38	0.38	0.584	35%	5%	262.3	448.8	241.5	1423.7	1423.7	Viscosity too low T_{50}= 2.4s), should reduce w/p
4	35%	0.36	0.36	0.554	35%	5%	255.5	461.4	248.3	1423.7	1423.7	Good, FINAL MIXTURE