

Maximizing SCM Content of Blended Cements

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Abstract - Today Portland cement substitutes known as supplementary cementitious materials or SCMs are used to improve the performance while reducing the environmental footprint of concrete. There are several factors that impact the amount of SCMs that can be added to concrete while maintaining its basic integrity. This paper describes a newly developed framework for optimizing the substitution of cement with SCMs in concrete. This framework has been developed based on recent testing results and clearly indicates that paying close attention to cement and SCM particle size distributions and the corresponding packing density of the combined ingredients will allow for an optimization of the cement and SCMs in concrete. This framework has been developed on the basis of several independent laboratory studies and can be adapted as a base for evaluating and optimizing any combination of cement and SCMs. The means to produce cement / SCM blends with the optimized particle size distributions with existing equipment configurations are also explored.

I. INTRODUCTION

Concrete is the most widely used commodity in the world after water and is being used in ever-increasing amounts, particularly in developing countries to build infrastructure. The production of Portland cement – the main strength producing component of concrete – has increased proportionately and dramatically to meet demand. The cement industry today generates approximately 5% of the anthropogenic CO₂ emissions worldwide. Companies around the world are looking for means to reduce the carbon footprint of concrete and cement. The best way to improve concrete’s carbon footprint is to make it with less Portland cement. Substituting Portland cement with supplementary cementitious materials (SCMs) is one means.

Common SCMs include fly ash, slags, and natural pozzolans. Fly ash is a waste product from coal combustion, typically from coal fired power plants. Slags are waste products from metal production, e.g., iron and steel. Natural pozzolans are found in nature as volcanic ashes, but can also be manufactured by calcining clays and shales. These SCMs are often classified together as “pozzolans” because they include amorphous silica that reacts with excess lime released during Portland cement hydration. Limestone can also be used as a partial cement substitute. The higher the level of SCMs contained in the blended cement and corresponding concrete, the better from both a cost and carbon footprint perspective.

Blended cements offer several advantages over pure Portland cements when making concrete:

- They can achieve similar or superior structural integrity;
- Have a lower carbon footprint;
- Can be more cost effective to produce; and
- Can utilize waste material streams from other industries.

The authors propose that SCMs can be most effectively used as cement substitutes when the particle size distributions (PSDs) of the cement and SCM fractions are optimized to complement each other. This paper describes the means to increase the content of SCMs in blended cements and concrete, including: (1) a simple analytical framework for predicting permissible SCM replacement levels; (2) case studies that validate the analytical framework; and (3) industrially feasible manufacturing systems for making optimized blended cements.

Ordinary Portland cement (OPC) is made up of finely ground calcium silicate particles. These particles react with water to form calcium silicate hydrates (hydration reactions) which interlock providing concrete its strength. Cement needs to be ground fine enough to allow the majority of the cement particles to fully react. Today cement is ground in various types of mills and size classified primarily with dynamic air separators giving a typical PSD as shown in Fig. 2. SCMs are usually processed for use in concrete through the same means, and usually have PSDs similar to Portland cement.

The water demand, or more simply, the water content of concrete is expressed as a unitless weight fraction (w/c) which is the weight of water divided by the weight of cement. When SCMs are added to the Portland cement, the water content of the concrete is adjusted to include the SCMs (w/cm), that is the weight of water per weight of cementitious materials (Portland cement plus SCMs).

Water serves a dual purpose in concrete, it is a necessary ingredient in the hydration reactions but also acts as a lubricant that separates the particles in concrete and allows the fresh concrete to flow. The required flowability of concrete usually determines the amount of water that is used. Excess water, required only for flow, does not react and remains as small water pockets in the concrete. These water pockets create voids in the concrete and can reduce its strength and durability.

The foregoing principles are often in conflict and cannot be satisfied simultaneously. For example, increasing cement fineness simultaneously increases reactivity and water demand, which have opposite effects on concrete strength. This is equally true for OPC as it is for blended cements. Therefore there is an inherent contradiction between grinding cement finer (which requires more water for coating and lubricating the cement particles) and controlling the water content of the concrete to maximize strength.

Recent studies involving independent particle size selection of cement and SCMs allow us to break this contradiction. The PSDs of the cement and SCMs blends are adjusted to maximize the particle packing density. This minimizes the void volume in the blended cement, thus requiring less water for flow. If in addition, a portion of the very fine cement particles are replaced with very fine SCM particles, cement flocculation is decreased which lowers water demand further. Reducing the water demand of the concrete produces denser, less porous, and stronger concrete. Both also provide the additional benefits of reduced shrinkage and ion permeability, which further enhances concrete strength and durability.

Particle size distributions that maximize packing densities are defined mathematically by a Fuller distribution. This is an idealized mathematical particle size distribution model that is applicable to all particles in concrete, in which smaller particles fill the voids around and between larger particles. The Fuller distribution is defined by (1), where D represents the maximum particle size in the mixture and P_i represents the percentage of particles finer than size d_i . A typical value for the exponent n is 0.45. The equation is dimensionless.

$$P_i = \left(\frac{d_i}{D} \right)^n * 100\% \quad (1)$$

The Fuller distribution is a theoretical, or ideal, particle size distribution that provides dense packing of particles and is also used for aggregate sizing in concrete.

II. ANALYTICAL FRAMEWORK

The framework developed for predicting permissible SCM replacement levels was derived from empirical strength data across a wide range of SCM substitution levels. The simplified analytical framework includes: (1) three fundamental design principles; (2) a procedure to develop an optimization score; and (3) a method for predicting permissible SCM replacement levels. A “permissible” SCM replacement level for a blended cement means the blended cement will reliably provide adequate strength, acceptable water demand, and other performance criteria based on predetermined standards. Certain concrete applications may require different performance criteria, in these cases the framework may need to be adjusted for those specific situations.

A. Three Fundamental Design Principles

The three fundamental design principles are:

1. Maintain a broad particle size distribution (PSD) (e.g., a Fuller distribution);
2. Minimize the quantity of coarse Portland cement particles (>24 μm); and

3. Minimize the quantity of overly fine Portland cement particles ($<8 \mu\text{m}$).

Large Portland cement particles ($> 24 \mu\text{m}$) do not fully hydrate within a specified time duration (e.g., 91 days) and essentially become “wasted cement”. On the other hand, fine Portland cement particles increase water demand as a result of excessive surface area and flocculation without providing a corresponding strength increase. Nevertheless, a broad particle size distribution including coarse ($>24 \mu\text{m}$) and fine ($<8 \mu\text{m}$) particles, as defined by the Fuller distribution, is required to maximize particle packing density. Therefore, a well-optimized blend will have a minimum amount of improperly sized cement particles (provided by a narrow PSD cement). The blend would also include fine and coarse SCM particles to improve the packing density according to the Fuller distribution, ensuring a low water demand.

B. Obtaining an Optimization Score Using The Three Fundamental Design Principles

The authors found, based on an analysis of empirical data, that the three fundamental design principles were not equal in effect and have therefore been weighted as follows:

Principle 1, Maintain a broad particle size distribution – 1.5 (maximum score)

Principle 2, Minimize oversized cement particles – 1.5 (maximum score)

Principle 3, Minimize undersized cement particles – 1.0 (maximum score)

In the following discussions, cement blends in compliance with a given design principle are awarded the maximum score. Cement blends in violation of a given design principle are awarded a score of “zero”. Cement blends in partial compliance with a given design principle are awarded a partial score between zero and the maximum score. The optimization score for a blended cement is the sum of all three scores. As shown by the case studies and other empirical data, the optimization score is easy to determine and fairly accurate. Increasing scores indicate the ability to substitute more SCMs for ordinary Portland cement.

The data also demonstrates that the optimization score is largely independent of the type of SCM that is utilized and therefore very robust as a predictive tool. The following case studies indicate that blended cements in compliance with all three fundamental design principles produced similar compressive and flexural strengths when using various combinations of SCMs. This is particularly surprising since the SCMs utilized (GGBFS, Class F fly ash, steel slag, and limestone) have very different chemistries and reactivities. The work in this paper is based primarily on optimizing blends of cement and SCMs to obtain equivalent strengths in concrete. Other properties of the concrete such as sulfate resistance and freeze thaw durability are believed to be improved through this optimization process; however, specific performance requirements will need to be taken into account by the practitioner as well.

C. Predicting Permissible SCM Replacement Levels Using the Optimization Score

The permissible SCM replacement level for a blended cement can be fairly accurately estimated by comparing its optimization score with optimization scores for the blended cements in the case studies below. Fig. 1. demonstrates how the 4 case study results, with SCM replacement levels of 20%, 35%, 55%, and 75% respectively, compare to their optimization scores. Pure, 100% ordinary Portland cement (OPC) is used as the baseline (0% SCM replacement) with an optimization score of 1 as explained below.

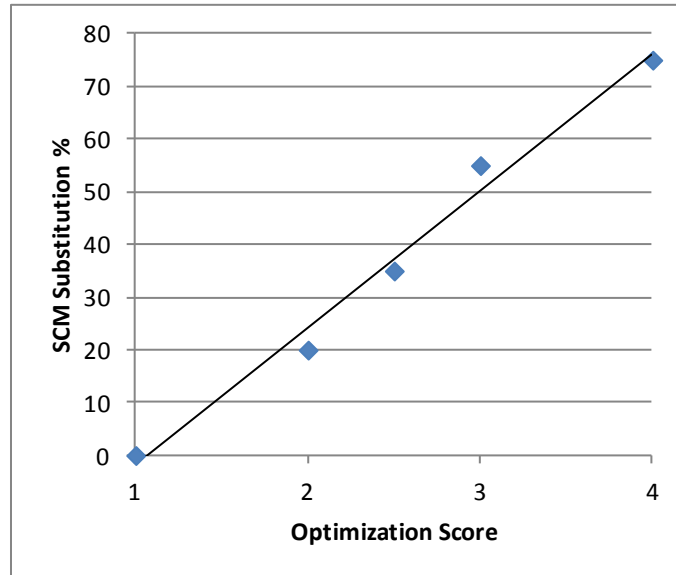


Fig. 1. Comparison of optimization scores and achievable SCM substitution rates

III. CASE STUDY COMPARISONS

A. Base Case - Ordinary Portland Cement (Optimization Score of 1.0)

At one end of the spectrum, a typical OPC (Type I-II) is represented by the PSD chart in Fig 2. This OPC has a d_{90} (90% of particles less than) 40-45 μm , a d_{10} (10% of particles less than) 1-2 μm , and a PSD narrower than a Fuller distribution. Fuller distributions for cement particles are difficult to obtain using conventional classification techniques typical to cement manufacture.

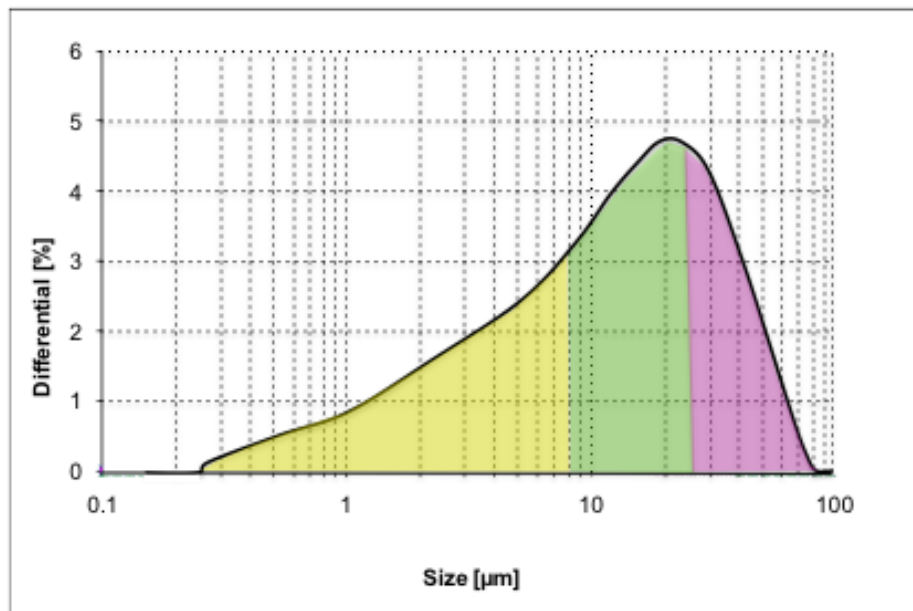


Fig. 2. A typical particle size distribution chart for ordinary Portland cement (OPC)

The typical OPC, as illustrated in Fig. 2., is in substantial (but not total) compliance with Principle 3 because the PSD, though broad, is narrower than a Fuller distribution. This OPC violates Principles 2 and 3 because the yellow shaded area

(particles $<8 \mu\text{m}$) and pink shaded area (particles $>24 \mu\text{m}$) consist entirely of Portland cement particles. Thus, its optimization score is estimated by the authors to be 1.0 ($1.0 + 0.0 + 0.0$). The low optimization score may explain why simple blended cements consisting of OPC and separately processed SCM can show a drop in strength, particularly early strength, when compared to 100% OPC at even modest substitutions in OPC of 15-25%. For this reason it is customary to increase the total binder content in concrete to make up for the drop in strength (e.g., 500 lbs. of 100% OPC in a cubic yard of concrete might be replaced with 600 lbs. of blended cement consisting of 450 lbs. of OPC and 150 lbs. of fly ash).

B. Case Study 1 - 80% Cement / 20% SCM Blend (Optimization Score of 2.0)

A first binary blended cement of the case studies with 80% Portland cement and 20% SCM was made using a fine cement and a coarse fly ash fraction represented by the two PSD charts in Fig. 3. & 4.

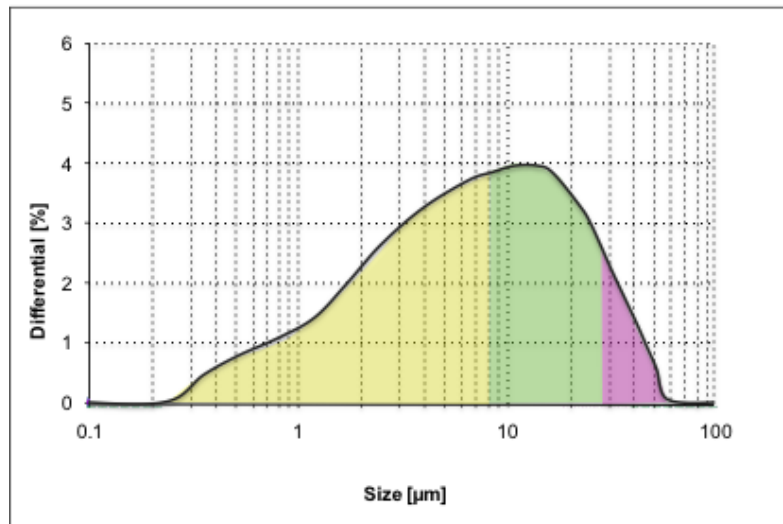


Fig. 3. Fine OPC particle size distributions for 80/20 blended cements

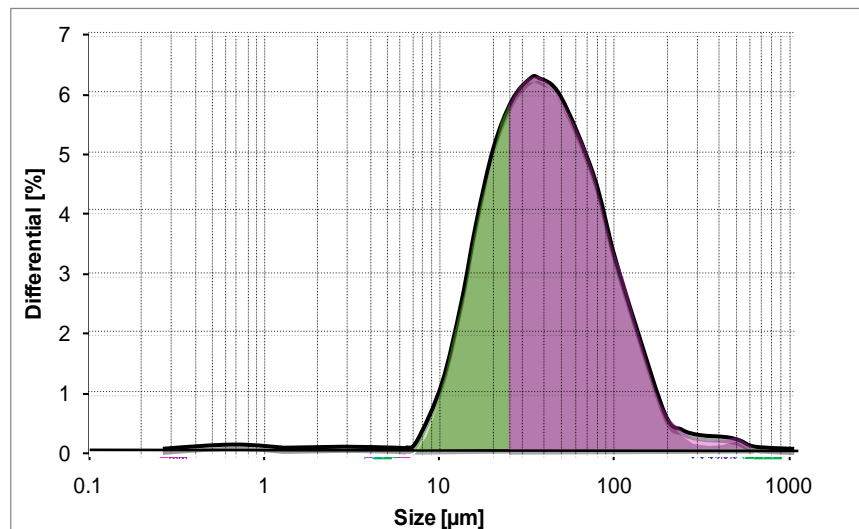


Fig. 4. Coarse flyash particle size distributions for 80/20 blended cements

This first binary blend is in substantial, but not total, compliance with Principle 2 due to the smaller but significant fraction of coarse cement particles ($>24 \mu\text{m}$) in the shaded purple area. It violates Principle 3 due to the large amount of very fine cement particles ($<8 \mu\text{m}$) in the shaded yellow area; and substantially, but not entirely, complies with Principle 1 because the coarse fly ash particles in the shaded purple area broadens the overall PSD of the blend, but not to the extent of a Fuller distribution. The estimated score is 2.0 ($1.0 + 1.0 + 0.0$), which explains why this binary blend had similar strength at all ages

compared to the control cement consisting of 100% OPC. This is an improvement over simple blends of 80% OPC and 20% fly ash as illustrated in the base case, which typically show a loss of early strength compared to 100% OPC.

The National Institute of Standards and Technology (NIST) under the direction of Dale P. Bentz tested four different binary blends containing 80% Portland cement and 20% Class F fly ash. A complete description of methodology and results is contained in the NIST Report [1]. Further information relating to strength, rheology, and other properties of the binary blends is contained in Bentz et al [2], and Bentz et al [3].

As summarized in Table I, one of the 80:20 binary blends had essentially the same strength as the 100% OPC control at all ages (1, 3, 7, 28, 91, and 182 days) and required almost no water reducer (HRWR) to maintain adequate flow. For comparison, two of the binary blends had greater strength than the 100% OPC control at all ages but required a significant quantity of water reducer to maintain adequate flow. All cement materials had a w/cm ratio of 0.35 (normalized for volumetric rather than weight substitution of fly ash due to the lower specific gravity of fly ash compared to cement; the w/cm of the binary blends on a weight basis was actually higher than 0.35).

Table I
Mortar strength results of various 80% Portland cement and 20% flyash blends

Cement Material	1-day (MPa) (psi)	3-day (MPa) (psi)	7-day (MPa) (psi)	28-day (MPa) (psi)	91-day (MPa) (psi)	182-day (MPa) (psi)	HRWR g/100 g cem
OPC Control	36.7 5320	54.4 7900	63.6 9220	80.3 11640	84.7 12280	86.0 12470	0.0
Cement 7 Fly ash 4	36.7 5320	50.8 7360	63.5 9220	78.1 11330	89.8 13020	91.8 13310	0.05
Cement 8 Fly ash 3	53.6 7770	68.5 9940	80.1 11620	89.7 13010	93.9 13620	99.6 14440	0.80
Cement 9 Fly ash 2	54.5 7910	66.7 9680	78.4 11370	92.9 13470	94.3 13680	96.2 13960	1.00
Cement 10 Fly ash 5	66.1 9590	76.3 11070	85.9 12460	102 14740	107 15510	105 15250	1.00 (no flow)

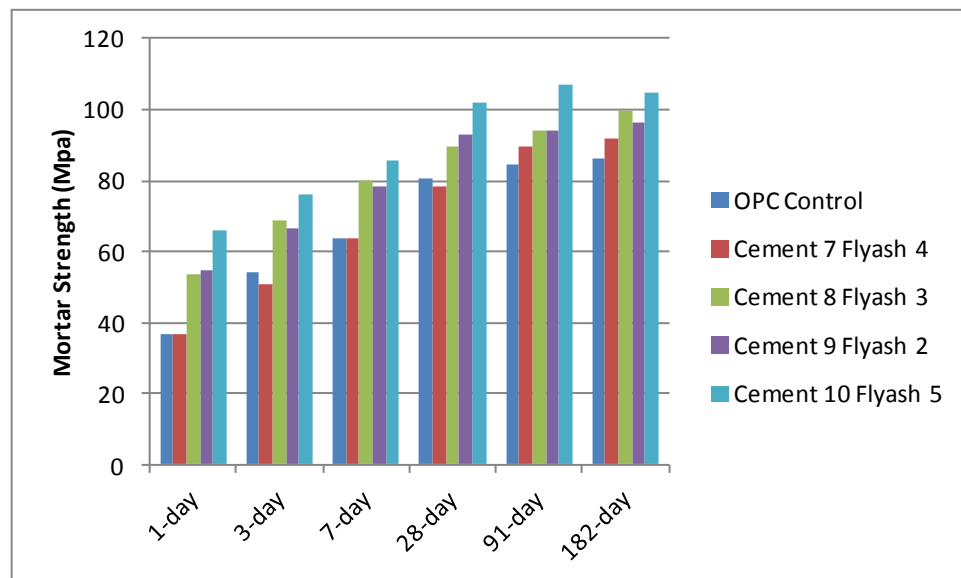


Fig. 5. Mortar strength results from different 80% Portland cement and 20% flyash blends

The main manufacturing steps for making the above binary blend with 20% SCM, are: (1) milling cement clinker to

provide a fine cement fraction with a desired d_{90} (e.g., 10-20 μm) using known mills, such as a ball mill, vertical roller mill, or roll press; (2) milling and/or classifying one or more SCMs to provide a coarse SCM fraction with a desired d_{10} (e.g., 5-20 μm); and (3) blending the fine cement and coarse SCM fractions prior to use in concrete.

C. Case Study 2 - 65% Cement / 35% SCM (Optimization Score of 2.5)

A second binary blended cement of the case studies with 65% Portland cement and 35% SCM was made using fine cement and coarse fly ash fractions represented by the following two PSD charts (Fig. 6. & 7.).

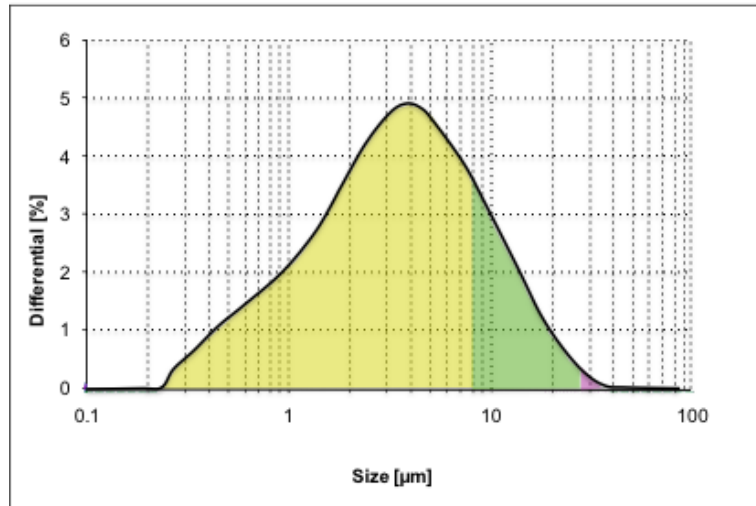


Fig. 6. Fine OPC particle size distributions for blended cement 2 (65 / 35 Blend)

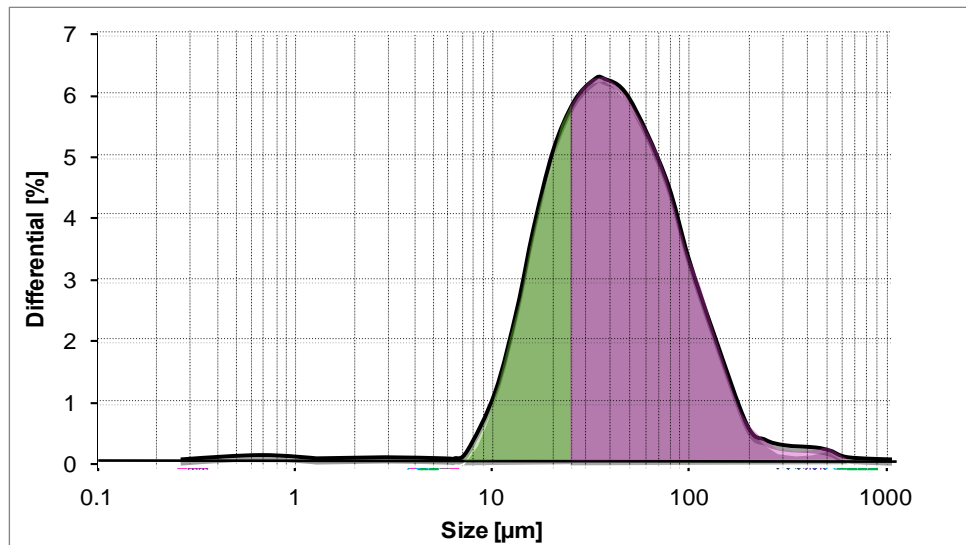


Fig. 7. Coarse Flyash particle size distributions for blended cement 2 (65 / 35 Blend)

This second binary blend fully complies with Principle 2 due to the insignificant quantity of coarse cement particles ($>24 \mu\text{m}$) in the shaded purple area of Fig. 6.; violates Principle 3 due to the very large amount of very fine cement particles ($<8 \mu\text{m}$) in the shaded yellow area of Fig. 6.; and substantially, but not entirely, complies with Principle 1 because the high quantity of coarse fly ash particles in the shaded purple area of Fig. 7. broadens the overall PSD of the blend, but not to the extent of a Fuller distribution. The estimated score is 2.5 (1.0 + 1.5 + 0.0), which explains why this binary blend, at 65% cement and 35% fly ash, had similar strength at all ages when compared to the control cement consisting of 100% OPC. This second blend also had a higher SCM content compared to the first binary blend which only had a score of 2.0.

NIST also tested four binary blends containing 65% Portland cement and 35% Class F fly ash and one blend containing 65% Portland cement and 35% Class C fly ash. Details of the test results are also contained in the references stated above [1]-[3].

As summarized in Table II, one of the 65:35 binary blends had essentially the same strength as the 100% OPC control at all ages (1, 3, 7, 28, 91, and 182 days) and required a modest but acceptable amount of water reducer (HRWR) to maintain adequate flow. The other 65:35 binary blends required less water reducer but generally had lower strength at all ages. All cement materials had a w/cm ratio of 0.35 normalized for volumetric substitution.

Table II
Mortar strength results of various 65% Portland cement and 35% flyash blends

Cement Material	1-day (MPa) (psi)	3-day (MPa) (psi)	7-day (MPa) (psi)	28-day (MPa) (psi)	91-day (MPa) (psi)	182-day (MPa) (psi)	HRWR g/100 g cem
100% OPC Control	36.7 5320	54.4 7900	63.6 9220	80.3 11640	84.7 12280	86.0 12470	0.0
Cement 9 Class C ash	38.8 5620	51.4 7460	61.4 8910	79.6 11540	85.9 12450	90.9 13180	0.67
Cement 7 Fly ash 3	27.4 3980	39.7 5780	51.8 7380	69.7 10100	79.2 11480	90.9 13170	0.00
Cement 8 Fly ash 2	37.9 5500	48.0 6960	59.3 8600	65.6 9510	77.1 11180	81.8 11860	0.37
Cement 9 Fly ash 5	39.0 5660	50.9 7380	58.3 8460	70.0 10150	82.9 12030	88.9 12890	0.48
Cement 10 Fly ash 4	44.6 6460	53.4 7750	64.8 9400	72.4 10500	80.6 11690	83.3 12080	0.67

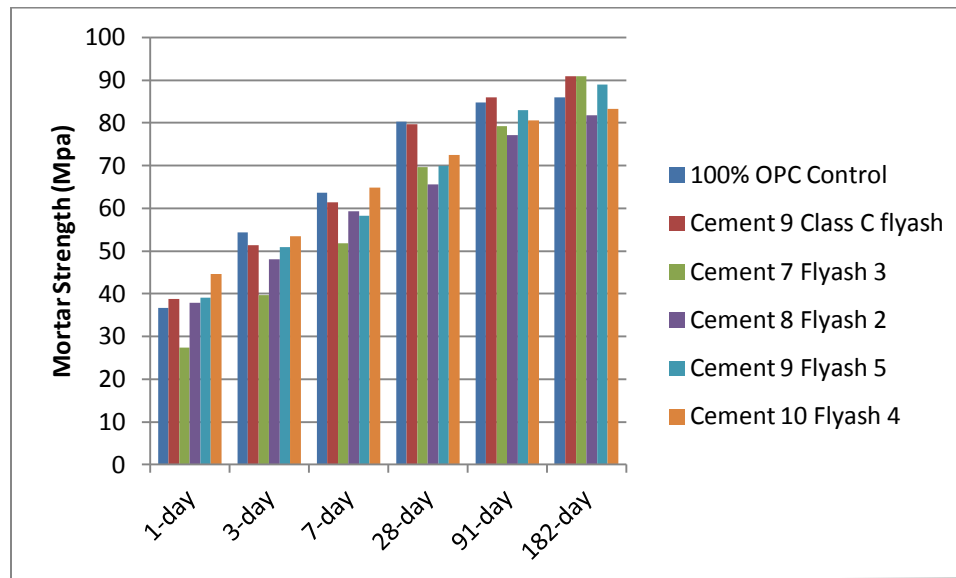


Fig. 8. Mortar strength results from different 65% Portland cement and 35% flyash blends

The manufacturing processes for this 35% SCM blend are essentially the same as for the 20% substitution above, just grinding the cement a little finer and adding more coarse SCM.

D. Case Study 3 - 45% Cement / 55% SCM (Optimization Score of 3.0)

The third case study involves a ternary blended cement with 55% SCM and 45% Portland cement. The cement component was an ordinary, commercial cement with a particle size distribution as shown in Fig. 9. The two SCMs had very tight particle size distributions selected as a coarse and a fine SCM as shown on the left and right sides in Fig. 10.

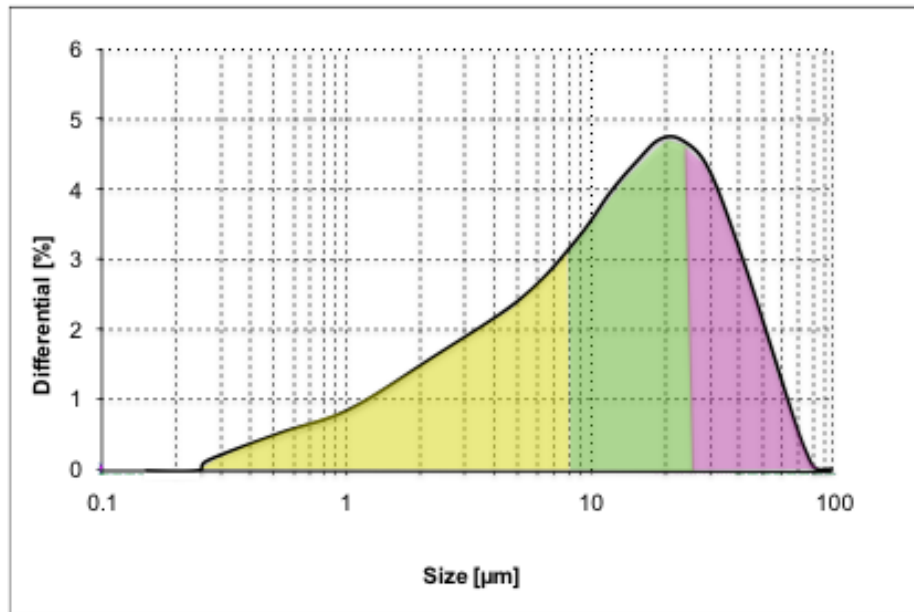


Fig. 9. Particle size distribution for the cement used for blended cement 3 (45 / 55 Blend)

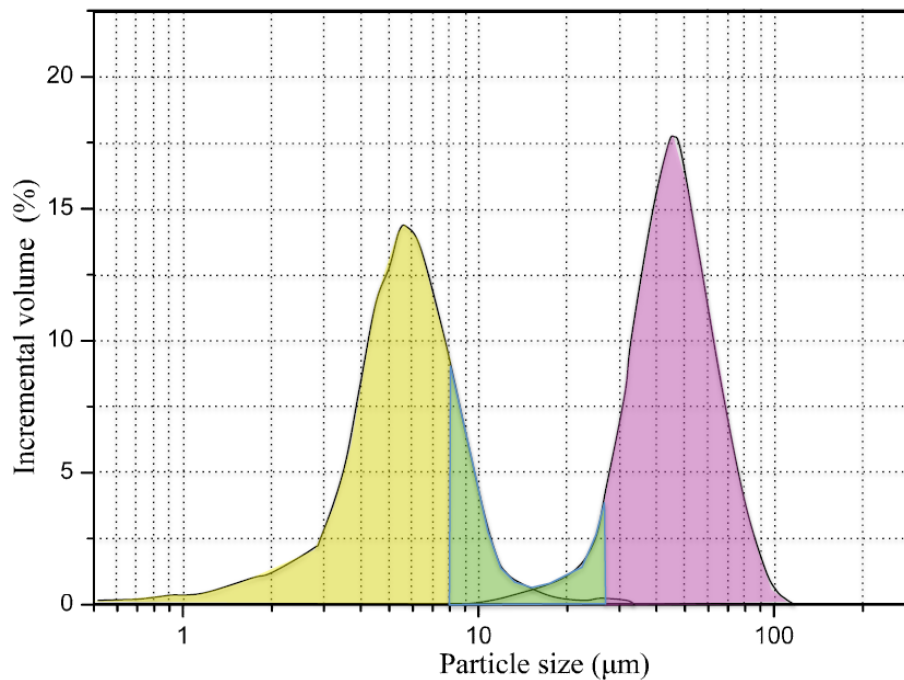


Fig. 10. Particle size distributions for the 2 SCMs used for blended cement 3 (45 / 55 Blend)

This ternary blend substantially, but not fully, complies with Principle 2 due to the smaller but still significant fraction of coarse cement particles ($>24 \mu\text{m}$) in the shaded purple area in Fig. 9. It partially complies with Principle 3 due to the significant quantity of very fine cement particles ($<8 \mu\text{m}$) in the shaded yellow area of Fig. 9. It complies with Principle 1 because the high quantity of very fine and coarse SCM particles in the shaded yellow and purple areas (Fig. 10.) broadens the overall PSD of the blend to approach a Fuller distribution. The estimated score is 3.0 (1.5 + 1.0 + 0.5), which explains why

this ternary blend had higher SCM substitution (55%) when compared to the second binary blend (35%) with a score of 2.5.

Researchers at South China University tested five different ternary blends containing 45% Portland cement and 55% SCM selected from GGBFS, fly ash, steel slag, and limestone. Details of the methodology and test results are described in the references [4]. A control cement consisting of 100% OPC was tested by the same researchers and described in Zhang, et al. [5]. The comparative strength results are contained in Table III and shown graphically in Fig. 11.

Table III
Mortar strength results of various 45% Portland cement and 55% SCM blends

Cement Material	Compressive Strength (MPa)		Flexural Strength (MPa)	
	3-day	28-day	3-day	28-day
100% OPC Control	24	45	5.8	9.5
Fine GGBFS 25% OPC 45% Coarse GGBFS 30%	26.5	49.2	6.8	9.8
Fine GGBFS 25% OPC 45% Coarse F ash 30%	25.6	47.3	6.5	9.7
Fine GGBFS 25% OPC 45% Coarse steel slag 30%	26.6	48.2	6.8	9.3
Fine GGBFS 25% OPC 45% Coarse limestone 30%	22.7	44.8	5.1	9.1
Fine GGBFS 20% Fine F ash 5% OPC 45% Coarse GGBFS 30%	24.9	45.5	6.4	9.4

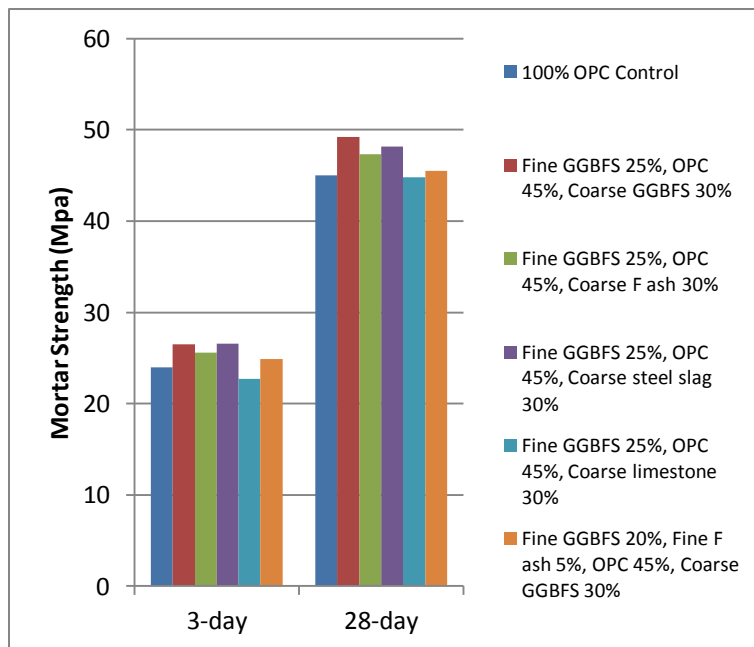


Fig. 11. Mortar strength results from different 45% Portland cement and 55% SCM blends

The main manufacturing steps for making the ternary blend above are: (1) obtaining or making OPC; (2) milling the fine SCM using known milling technology to a desired d_{90} (e.g., 5-8 μm); (3) milling and/or classifying one or more SCMs to provide a coarse SCM fraction with a desired d_{10} (e.g., 15-25 μm); and (4) blending the OPC with the fine and coarse SCM

fractions.

E. Case Study 4 - 25% Cement 75% SCM (Optimization Score of 4.0)

The use of ordinary Portland cement in case study 3 gave the blend a large amount of cement fines and a portion of oversized cement particles. Gap grading can overcome these limitations, by removing the unwanted size fractions. This is done in the lab, by carefully separating out the particles of interest and discarding the rest. The gap-graded, ternary blended cement of the case studies (with 75% SCM and 25% Portland cement) is in substantial compliance with Principles 1-3 and has an optimization score of 4.0 (1.5 + 1.5 + 1.0). The PSDs of the three components are shown in the chart in Fig 12.

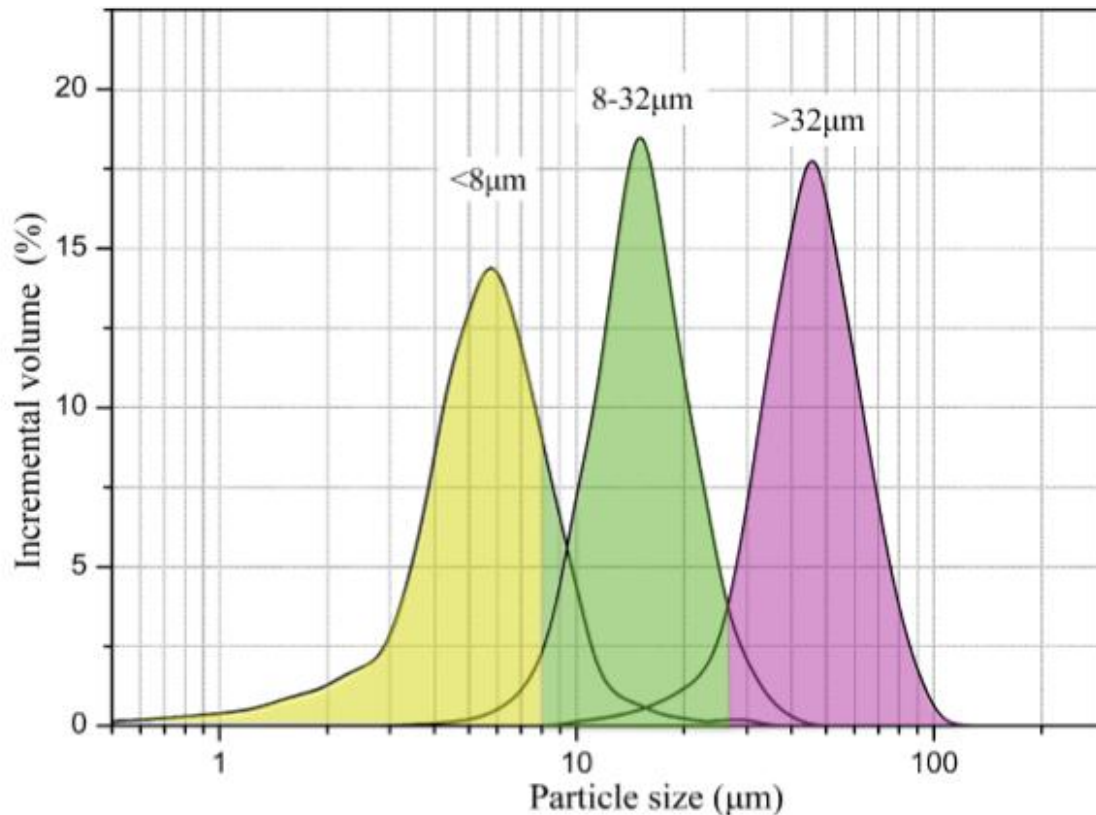


Fig. 12. Particle size distributions for a gap graded ternary blended cement (25 / 75 Blend)

The three curves represent the three components of the gap-graded ternary blend: a fine SCM fraction (left), a narrow PSD Portland cement fraction (center), and a coarse SCM fraction (right). The yellow shaded area represents fine particles below 8 μm , the green shaded area represents intermediate particles between 8-24 μm , and the purple shaded area represents coarse particles above 24 μm . The blend substantially complies with Principle 1 because the overall PSD of the blend approximates a Fuller distribution even though it consists of three separate fractions with narrow but complementary PSDs. This blend substantially complies with Principles 2 and 3 because the yellow and pink shaded areas mainly consist of SCM particles and are substantially devoid of Portland cement particles.

Researchers at South China University [4], [5] tested five gap-graded ternary blends containing 25% Portland cement and 75% SCM selected from GGBFS, fly ash, steel slag, and limestone. The comparative strength results are contained in Table IV and shown graphically in Fig 13.

Table IV
Mortar strength results of various 25% Portland cement and 75% SCM blends

Cement Material	Compressive Strength (MPa)		Flexural Strength (MPa)	
	3-day	28-day	3-day	28-day
100% OPC Control	24	45	5.8	9.5
Fine GGBFS 36% Narrow PSD cem 25% Coarse GGBFS 39%	23	43	6.6	10.0
Fine GGBFS 36% Narrow PSD cem 25% Coarse F ash 39%	19	42	5.8	9.5
Fine GGBFS 36% Narrow PSD cem 25% Coarse steel slag 39%	22	44	6.2	9.6
Fine GGBFS 36% Narrow PSD cem 25% Coarse limestone 39%	18.5	36	5.8	9.7
Fine steel slag 36% Narrow PSD cem 25% Coarse steel slag 39%	18	38	5.7	9.5

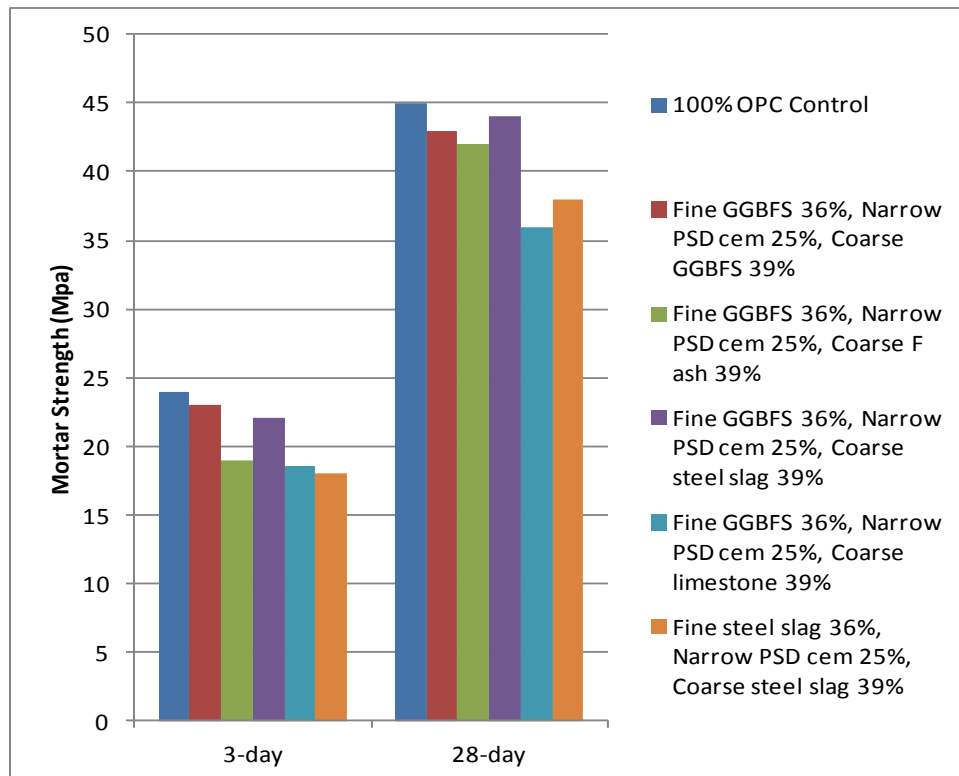


Fig. 13. Mortar strength results from different 25% Portland cement and 75% SCM blends

The ternary blend of Case Study 4 is not industrially feasible at this time using existing equipment because it is difficult to make the narrow PSD cement fraction at an acceptable yield. The ternary blend of Case Study 3 is therefore a compromise solution proposed by Zhang et al. at South China University [5].

F. Summary of Findings

Based on the foregoing, the permissible SCM content of virtually any blended cement can be predicted by first determining its optimization score and then comparing it to the optimization scores of known cements determined in the case studies above and which are summarized in Table V and shown graphically in Fig. 1.

TABLE V
Summary of optimization scores and OPC content

Cement Material	SCM Content	Cement Content	Optimization Score
OPC	0%	100%	1.0
First Binary Blend	20%	80%	2.0
Second Binary Blend	35%	65%	2.5
Second Ternary Blend	55%	45%	3.0
First Ternary Blend	75%	25%	4.0

The fundamental principles that are used to assess the cement / SCM blends provide the optimization score and point towards the level of SCM substitution that can be achieved. In an ideal situation, such as case study 4, each individual component would have a closely controlled particle size distribution. The combination of which would provide the desired Fuller distribution. In this case the optimum packing density would likely be achieved and the water to cement ratio held at a minimum. The cement particles would be in a range to provide their maximum strength to the mix thus allowing the higher substitution rate of SCMs. As noted these conditions may be difficult to achieve in industrial operations.

However, analyzing current cement / SCM blends against these principles should allow practitioners to evaluate their current blends and use the principles stated here for further optimization.

IV. MANUFACTURING

The binary blends according to Case Studies 1-2 are relatively easy to manufacture using known manufacturing equipment. The ternary blends according to Case Study 3 were offered as a compromise solution to the ternary blends of Case Study 4, which are difficult to produce because a tightly controlled narrow PSD cement (8 – 24 μm) is necessary but difficult to make. The proposed compromise in Case Study 3 used OPC in place of the narrow PSD cement of Case Study 4, with good results.

The authors propose a new compromise blend, which could allow for a high optimization score. This new compromise blend would include: a fine interground cement-SCM fraction and a coarse, potentially different, SCM fraction added after grinding.

The fine cement-SCM fraction is interground to a desired d90 to minimize the quantity of coarse cement particles above 24 μm , substantially or fully complying with Principle 2. The fine SCM sub-fraction reduces the quantity of fine cement particles below 8 μm , which increases (but does not fully reach) compliance with Principle 3. Blending the fine interground cement-SCM fraction with the coarse SCM fraction substantially or fully complies with Principle 1. Depending on the level of compliance with Principles 1-3, it should be possible for this new compromise blend to have an optimization score of 3.0 or higher, which should yield blended cements having at least 55% SCM levels as achieved in the ternary blend of Case Study 3.

An industrially feasible manufacturing system for making the new compromise blends is schematically illustrated in Fig. 14.

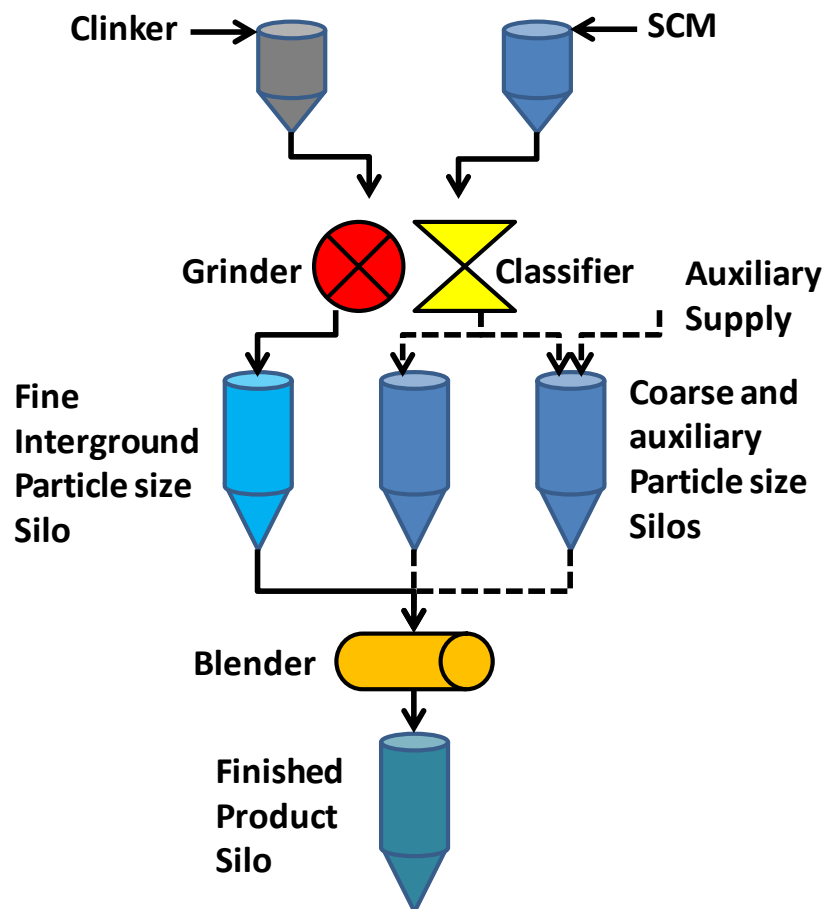


Fig. 14. Schematic for manufacturing a compromise blend for a high percentage of SCM substitution

The manufacturing steps for making the new compromise blends are simplified compared to the ternary blend of Case Study 3 and similar to those of the binary blends of Case Studies 1 and 2. First, cement clinker and an SCM are interground to provide a fine cement-SCM fraction with a desired d_{90} (e.g., 20-24 μm) using known mills, such as a ball mill, vertical roller mill, or roll press. Then one or more SCMs are independently milled and / or classified to provide a coarse SCM fraction with a desired d_{10} (e.g., 15-25 μm). Finally, the fine cement and coarse SCM fractions are blended together.

An optional auxiliary particulate material (such as an SCM or fine limestone, etc.) can be added at the ready mix plant as desired to adjust cement / concrete properties in a possible fourth step. This would permit a concrete manufacturer to supplement the compromise blend as desired with OPC or SCMs when making a particular concrete mix. For example, in cold weather or to otherwise boost strength, some additional OPC could be added at the ready mix plant. Alternatively, when it is desired to reduce the heat of hydration in thick-walled concrete or otherwise reduce reactivity, a quantity of SCM such as slag and/or fly ash could be added at the ready mix plant.

V. SUMMARY AND CONCLUSIONS

Reducing the use of ordinary Portland cement in concrete has multiple benefits to society, including a reduction of CO₂ emissions, lower cost concrete, and the utilization of various waste materials such as flyash and slag. The current practices for producing ordinary Portland cement and SCMs are not optimized for particle packing density, thus resulting in lower cement substitution rates. Ordinary Portland cement substitution can be optimized through tightly controlling the Portland cement particle size distribution and using particle packing principles to reduce the water demand of the concrete.

The performance of different Portland cement / SCM blends can be predicted based on the analytical framework presented. This framework only requires that the particle size distribution of the various blend components be known in advance. Several

case studies are examined that demonstrate the validity of the framework. The framework also provides insights for companies that wish to increase clinker substitution while maintaining concrete integrity.

Finally the production methods for cement and SCMs are briefly explored which gives information on what can and cannot be accomplished using existing equipment in cement and concrete plants today. It is shown that intergrinding OPC and SCM blends is often better than field mixing these components at the concrete plant. It is also shown that compromise blends can be produced with existing equipment, by paying careful attention to the particle sizes of the blended components. The application of these approaches should enable greater SCM substitution in the future, thus further reducing the carbon footprint of concrete.

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