Consider Functional Equivalence: A (*Faster)* Path to Upscaling Sustainable Infrastructure Materials Compositions

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Abstract

While alternative cement and binder chemistries are potential opportunities for addressing sustainability concerns associated with traditional portland cement concrete, the lack of guidance in existing materials testing and characterization hinders broader use of these emerging materials in transportation infrastructure renewal. This contribution considers the grand challenge in "upscaling" alternative cements and binder compositions. Specifically, discussion will center on options for establishing "functional equivalences", which can be used to rationalize the translation and adaptation of existing test methods to consider emerging materials. Challenges associated with direct application of existing methods will be briefly presented. In addition, specific examples of functional equivalence – ranging from plastic material characteristics to mechanical behavior and durability, considering a range of emerging cement and binder formulations – will be provided. By comparing alternative cements and binders to portland cement in a variety of contexts, these examples will serve as guideposts for a broader discussion of the evolution in testing and specification necessary for a "faster path" in upscaling emerging infrastructure materials technologies.

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I. INTRODUCTION

The shift from prescriptive specification of hydraulic cements (e.g., ASTM C150, C595) to performance-based specification (e.g., ASTM C1157) *should* offer greater opportunities for this use of a broader range of cement (or, more broadly "binder") compositions in concrete construction [1-3]. First introduced for blended cements in 1992, ASTM C1157 was broadened in 1998 to also encompass portland cements as well, providing a uniform set of performance criteria with no restrictions on the composition of the cement or its constituents [4]. Similarly, in recent years, American Concrete Institute (ACI) guidance regarding design of portland cement and blended concrete mixtures for durability has grown more reliant on performance measured during accelerated laboratory testing. As a result, alternative cements (ACMs) (or those not addressed in ASTM C150) should be increasingly viable alternatives to portland cements from a practical perspective.

Such cements may offer various benefits or improvements, including – of relevance to the topic of this conference – potential enhancements to the sustainability of concrete. For example, Figure 1 compares portland cement to a range of alternative cement (ACM) compositions, including calcium sulfoaluminate (CSA), CSA-belite (CSAB), calcium aluminate cements and blends (CAC), magnesium phosphate (MPC), and chemically activated (AA) binders in terms of embodied carbon dioxide (CO_2) [5]. The embodied CO_2 per ton of clinker or binder related to fuel consumption during manufacture and calcination of raw materials are determined explicitly. Each ACM shows a reduction in embodied CO_2 when compared to portland cement on a 1:1 replacement by mass basis. Additional potential advantages of ACMs vary with composition, but include rapid set, rapid strength development and/or high early strength, shrinkage compensation, and improved durability, including improved high temperature performance.

Yet despite the potential benefits, ACM usage remains very limited. In a recent survey conducted by AASHTO's Subcommittee on Materials, only 15 states reported any experience with ACMs [5]. Most instances of ACM use were small in scale, generally related to patching and repair applications. A few states – including California, Georgia, and Illinois – have placed some rigid pavement "test tracks" produced using ACMs. Other states cite concerns about unknown long-term performance as a primarily reason for their lack of ACM usage. While expressing a general lack of familiarity with the performance of ACMs, responding states specifically noted that the lack of data surrounding durability related to corrosion resistance, freeze/thaw durability, salt-scaling resistance and fatigue life represents a significant barrier to ACM usage.

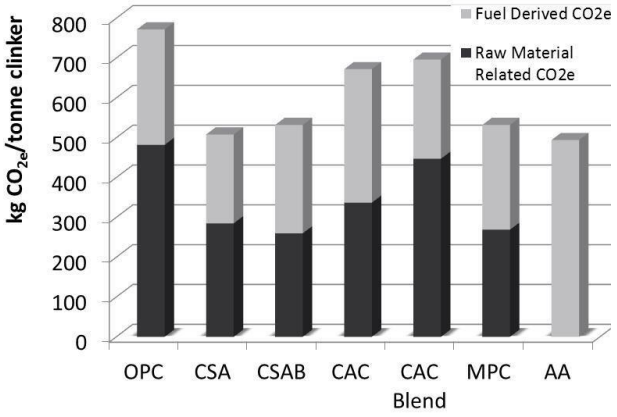

Figure 1. Comparison of embodied carbon dioxide between portland cement (OPC) and various ACMs, assuming a 1:1 by mass usage rate. Based upon [5].

Useful information regarding long-term performance in a range of applications will be derived (eventually) through evaluation and monitoring of existing ACM test tracks and from assessments performed at field exposure sites, such as the ACM concrete samples recently placed by the author and others at the US Army's field station at Treat Island, Maine [Figure 2]. Until then, laboratory-based accelerated testing remains a vital tool for materials assessment, screening, development, and specification.

Today, current standard accelerated test methods provided by ASTM and AASHTO for cement, mortars, and concrete fail to adequately provide for the preparation and testing of alternative cements and other binding materials [6-7]. Lack of guidance on material characterization, proportioning, and curing methods to establish "functional equivalence" among binders of different chemical composition, physical characteristics, and performance (particularly at early ages) prevents the establishment of test programs which assess material responses under accelerated exposure conditions in a manner which is as consistent and as unbiased as practical.

This lack of guidance on the appropriateness and implementation of standard test methods for ACMs increases the burden of risk to the materials producer, concrete provider, and owner and ultimately represents a significant impediment to the "upscaling" of ACM materials from the laboratory benchtop to practice. Thus, modernization of standard test methods is sorely needed [8]. This paper will describe how establishing functional

Figure 2. The first author with ACM concrete prisms placed at the US Army's outdoor field exposure site in Treat Island, Maine in August 2015.

equivalence is a critical step toward the modernization of existing test methods and the upscaling of ACM usage.

II. CONCEPT OF FUNCTIONAL EQUIVALENCE

Functional equivalence (FE) is a term routinely used in life cycle assessment (LCA) [e.g., 9,10]. When appropriately defined, an FE is an important means to compare alternative materials or, more often, systems. FE is defined based upon the specific needs of a project and typically encompasses the performance or function of the overall structure. When done appropriately, establishing a FE can provide a useful basis for comparison among options. Poorly defining FE or using performance metrics which are not appropriate for the project, undermines the utility of this approach [11].

Fortunately, the application of this concept of FE for accelerated testing of cementitious materials and mixtures is more straightforward than the more usual (and more complex) exercise in establishing FE for an entire building. For our purposes, the concept of FE can be used to compare alternative binders (i.e., materials) or concretes (i.e., systems).

For decades, compressive strength has been the *de facto* means of establishing functional equivalence among concrete mixtures. Today, assessments of compressive strength remains part of some accelerated durability test methods, including those incorporated into performance specifications for cement and concrete. For example, mortars prepared with uniform water-to-cement (w/c) and sand-to-cement (s/c) ratios must achieve a minimum compressive strength of 3000 psi prior to initiation of sulfate exposure during testing by ASTM C1012 [12]. It does not take much experience with cementitious materials to recognize that cementitious materials with identical compressive strength at a particular age can be produced from vastly different materials, vastly different proportions, and have vastly difference performance as measured through other metrics. Further, with regard to durability testing, compressive strength – while certainly an important performance criterion – links only indirectly (at best) to the factors which control durability.

II. STABLISHING FUNCTIONAL EQUIVALENCE IN ACCELERATED TEST METHODS: CURRENT PRACTICE

Because of its relationship to porosity which in turn governs transport properties, water-to-cement ratio – or more broadly, water-to-cementitious materials (w/cm) or more broadly still, water- to-binder (w/b) – is often a parameter which is specified when assessing durability in cement-based materials. Rather than using "job mix" proportions, many accelerated test methods mandate the proportionality between mix water and cementitious materials for consistency. Most often these ratios are given on a mass (M) basis:

$$\frac{w}{b} = \frac{M_{water}}{M_{binder}}$$

where the term M_{binder} is used for any potentially reactive binding material (e.g., cement, SCM or other finely divided mineral phase) and M_{water} represents the mass of water or the mass of activating solution. While not an explicit performance measure, w/b *is* related to range of properties, including workability, strength, and permeability, which *are* potential performance measures upon which FE may be established. As such, w/b can be viewed as a "stand in" for FE.

While the specific gravity (SG) of portland cements conforming to ASTM C150 vary within a relatively narrow range of perhaps 3.05 to 3.15, the specific gravity of ACMs ranges more broadly. As a result, when "functional equivalence" is established through specification of a w/c in an accelerated test method, the actual structure and properties of ACMs are likely quite different from that for portland cement. For example, consider the case where a w/c of 0.485 by mass is specified, as in ASTM C1012, which is

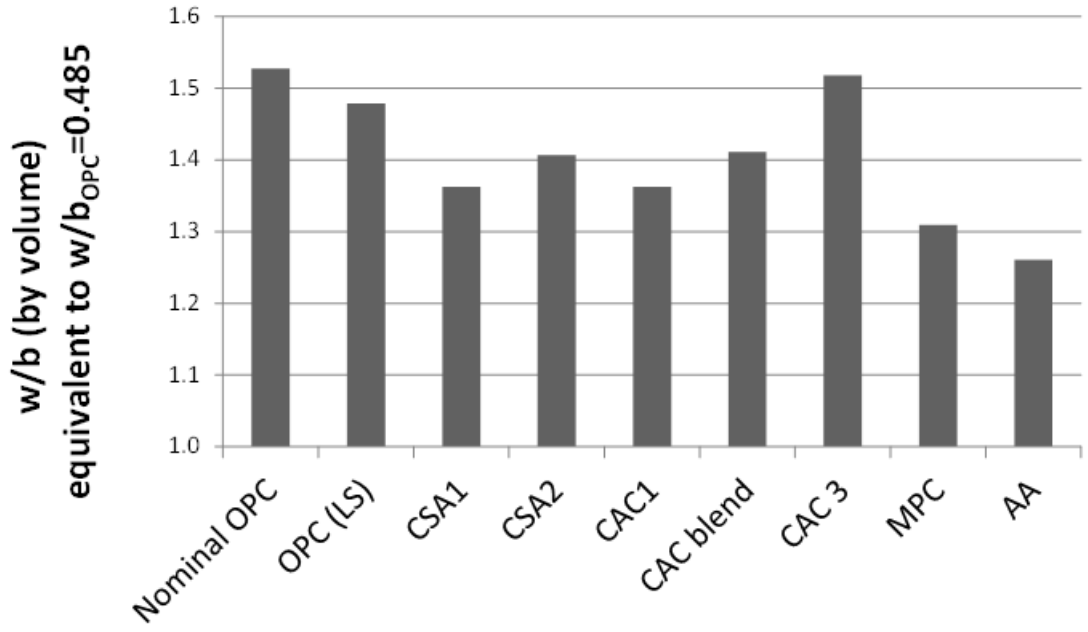

Figure 3. Comparison of initial w/b ratio by volume for pastes produced from a range of alternative cementitious materials at a 0.485 ratio by mass show large differences in water-filled porosity.

similar to other standard ASTM and AASHTO mortar test methods. Figure 3 shows the difference in the w/b *by volume* at the time of mixing (paste fraction only) for a range of ACMs, compared to ordinary portland cement with its nominal SG of 3.15 and modern Portland cements conforming to ASTM C150 which can contain up to 5% calcium carbonate and as a result have a slightly lower SG typically. By volume, these initial values range from 1.25 to 1.52, representing up to a ~20% difference in *initial* porosity. It is clear, then, that w/b by mass is an inappropriate means for establishing FE amongst modern cements.

Upon hydration or other reaction, the ratio of the volume of the products to the reactants in ACMs can also be quite different than that in portland cement hydration. With many ACMs, the nature of these reactions – the volume of product relative to reactant (at varying ages, under varying curing conditions) – has not been well-addressed through research. Also, in several classes of ACMs, the volume occupied by the reaction products can vary considerably within early ages (e.g., CSA cements which can initially produce expansion, CAC cements which can experience conversion). Therefore, even if w/b were specified by volume it is not clear that this is an effective and consistent means for establishing FE at the start of an accelerated test.

III. PLORING OPTIONS FOR ESTABLISHING FUNCTIONAL EQUIVALENCE

Potential options for establishing FE in cement-based materials are numerous, but an appropriate FE should ensure that the accelerated test method allows for consistent and representative comparison among ACMs, while also maintaining the integrity of the test method.

A. Establishing FE at Early Ages

Considering that all samples must be mixed, cast, compacted, and finished, it could be argued that FE should be established based upon early age behavior, such as consistency or flow. Today, high range water reducing chemical admixtures are routinely used in practice to alter flow behavior in concrete [e.g., Figure 4], to allow for effective compaction and finishing. While the use of such water-reducing admixtures may have ancillary effects on early hydration rates, ultimately their use should be favored – over the alternative of using excessively high (and practically irrelevant w/b) to achieve comparable early age properties – in cases where flow is too low at w/b used in practice or of relevance to the accelerated test method.

Indeed, in accelerated mortar bars tests (AMBT) used for assessing potential for damage by alkali silica reaction, when finely divided supplementary cementitious materials (i.e.,

Figure 4. The use of water-reducing admixtures can aid in establishing equivalent flow to facilitate sample casting at a range of binder compositions and w/b. Images above show flow test results for same binder at same w/b, without (top) and with (below) HRWR. [Photo courtesy of Behnaz Zaribaf.]

silica fume or metakaolin) are included in the mortar bars tested in ASTM C1567, high range water reducing admixtures (HRWR) are permitted. These are used at dosages to adjust flow to be consistent with the ordinary cement control, while maintaining a consistent w/b of 0.47 (with the water in the admixtures included as mix water). In that standard, while flow is adjusted to establish equivalence, the test method itself relies upon the rate and extent of reaction between the alkaline soak solution and the mortar. Thus, it can be viewed that the essential element of FE in ASTM C1567 remains w/b, as in its companion standard ASTM C1260 for cementitious mortars in the absence of SCMs.

Given that the use of HRWR is standard practice in modern concrete construction, that HRWRs are effective in plasticizing a range of ACMs without excessive retardation or bleeding, and that HRWR is already permitted in existing durability test specification (apparently without any problematic consequences, based upon lack of reports thereof in the literature), it may be argued that flow or slump adjustments through the use of HRWA should be more broadly permitted in modern test methods for cementitious materials. This would facilitate assessment of a broader range of binder compositions, without necessitating the development of an essentially parallel set of specifications (e.g., ASTM C1260 and ASTM C1567).

B. Establishing FE for Hardened Materials

Identifying means for establishing FE in hardened materials is a more challenging endeavor. Most accelerated durability tests involve the interaction between a porous cementitious material, typically a mortar or concrete, and some external source of aggression (e.g., water, salt solutions, sulfate solutions, alkaline solutions). As previously addressed, current test standards and materials specifications rely upon w/b or strength as a "stand in" for other properties (e.g., permeability, diffusivity) that govern the rate and extent to which aggressive species interact with the porous materials. However, specification of a w/b and strength are not effective means for establishing FE due to variations in intrinsic physical properties, such as SG and particle size, as well as the rate and extent of binder reactivity and the nature of the reaction products (as previously detailed.)

Therefore, a need exists to establish a basis for FE more directly related to transport properties. As others have previously detailed [e.g., 13,14], direct measurements of permeability and diffusivity – which could be measured for binders at a range of w/b to establish FE based upon coefficients describing rates of transport under those conditions – can be arduous to measure directly. This approach, due to the long duration of the tests (which would have to be performed on a range of sample compositions prior to the actual durability assessment), is impractical in terms of relatively routine assessments of material durability.

Electrical test methods, such as rapid chloride permeability and resistivity tests, are more rapid techniques used for indirect assessment of transport properties and can be quite useful for comparing among different material combinations and mix designs [15]. However, electrical test methods can be particularly sensitive to changes in pore solution and binding phase conductivity [16], which may result from the use of ACMs but which may not in practice

affect transport. As a result of these artifacts, the use of electrical methods as a basis for establishing FE is not appropriate.

Sorptivity testing is a potentially viable option for establishing FE prior to standard accelerated durability testing. Performed under a variety of conditions, standard assessments of sorptivity are unified in that the change in mass of a sample exposed to water is measured. A sorption rate can be determined when mass is measured over time, where different trends may be observed in the first few hours compared to later behavior (initial sorptivity rate vs. secondary sorptivity rate).

With regard to its use for FE, samples prepared at different w/b can be compared to identify proportions which provide reasonably similar behavior. One advantage of sorptivity testing over permeability and diffusivity testing is that these tests can typically be performed in a short period of time; the longest version of these tests takes 8 days to perform. Further, the property measured by these tests is directly related to the various common methods for assessing durability in the laboratory, which typically require interaction between the porous material and aggressive species from the surrounding environment.

However, changes are needed to implement sorptivity testing to establish FE. First, in their current form, most standard sorptivity tests, including ASTM C1585 [17], are specified for hydraulic cement-based materials, which excludes chemically activated ACMs, for example. Other test methods, such as ASTM C1757 [18], are intended for concrete, and their inclusion in a specification for mortars, such as for accelerated testing for alkali silica reaction (ASR) or sulfate resistance would require additional consideration and guidance to establish consistent and appropriate paste fractions. Others [19] have demonstrated that existing drying regimes are not specified stringently enough to allow for establishment of FE; this must be addressed.

Perhaps most problematic is that all current standard specification for sorptivity testing, including the two ASTM methods previously noted as well as similar tests described in RILEM TC116-PCD and BS-1881-122 [20,21], require samples to be conditioned in a drying environment occurring typically at high temperature, usually 50^{o}C but up to 105^{o}C. Water uptake during sorptivity testing occurs at early ages primarily by capillary action. As such, drying of the samples prior to water exposure, increases the rate and extent sorption by this means. ASTM C1585 addresses this by measuring both an initial sorption rate, which is sensitive to surface conditions and capillary suction, and also a secondary sorption rate, which is more representative of the rate of moisture transport within the bulk material. Secondary sorptivity rate appears to be the parameter more representative of the material structure and more representative of the rate and extent of interaction with ingressing aggressive species.

Temperature exposure and drying can also introduce cracking and changes in pore structure at various scales which can affect sorptivity [22]. It is also necessary to consider that the exposure to higher temperatures at early ages in particular can influence the rate and extent of chemical reactions occurring in relatively recently produced binders, as well as the structure and composition of the reaction products. Evaluation is necessary to develop appropriate guidance on sample drying regimes, considering age of drying, duration of drying, relative humidity, and temperature, which are appropriate for a broad range of binders. Such evaluation should also consider both mortars and concretes.

IV. RELIMINARY VALIDATION OF CONCEPT

The authors are *cautiously* optimistic on the use of secondary sorptivity rate as means for establishing FE, based upon a very small series of accelerated mortar bar tests for ASR. In this series, mortar bars and mortar cylinders were prepared with a known reactive aggregate using the same mix proportions (i.e., w/b, s/b) by mass. Expansion was monitored during exposure during the accelerated conditions described in ASTM C1260 [23], where the aggregate was expected to react. Initial and secondary sorptivity by ASTM C1585 as well as bulk sorption by ASTM C1757 were also measured.

As seen in Figure 5, a correlation between aggregate expansion, as facilitated by the availability of alkalis and water, and sorptivity can be observed. That is, for the same reactive aggregate and with the same mortar proportions, the lowest expansion is measured for the mortar with the lowest sorptivity, CSA1, as determined by both methods. The relationship between secondary absorption rate, in particular, seems to be reasonably well-correlated with expansion results, since those results relatively similar for OPC, CSA2, and CAC2, as are the 14-day mortar expansions. (AMBT results were not yet available for the AA binder which also displayed low sorptivity at these proportions.)

The approach previously discussed proposed using sorptivity to establish *a priori* FE, allowing appropriate w/b to be selected relatively rapidly. And, these tests will be performed in ACM mortars at a range of w/b to determine

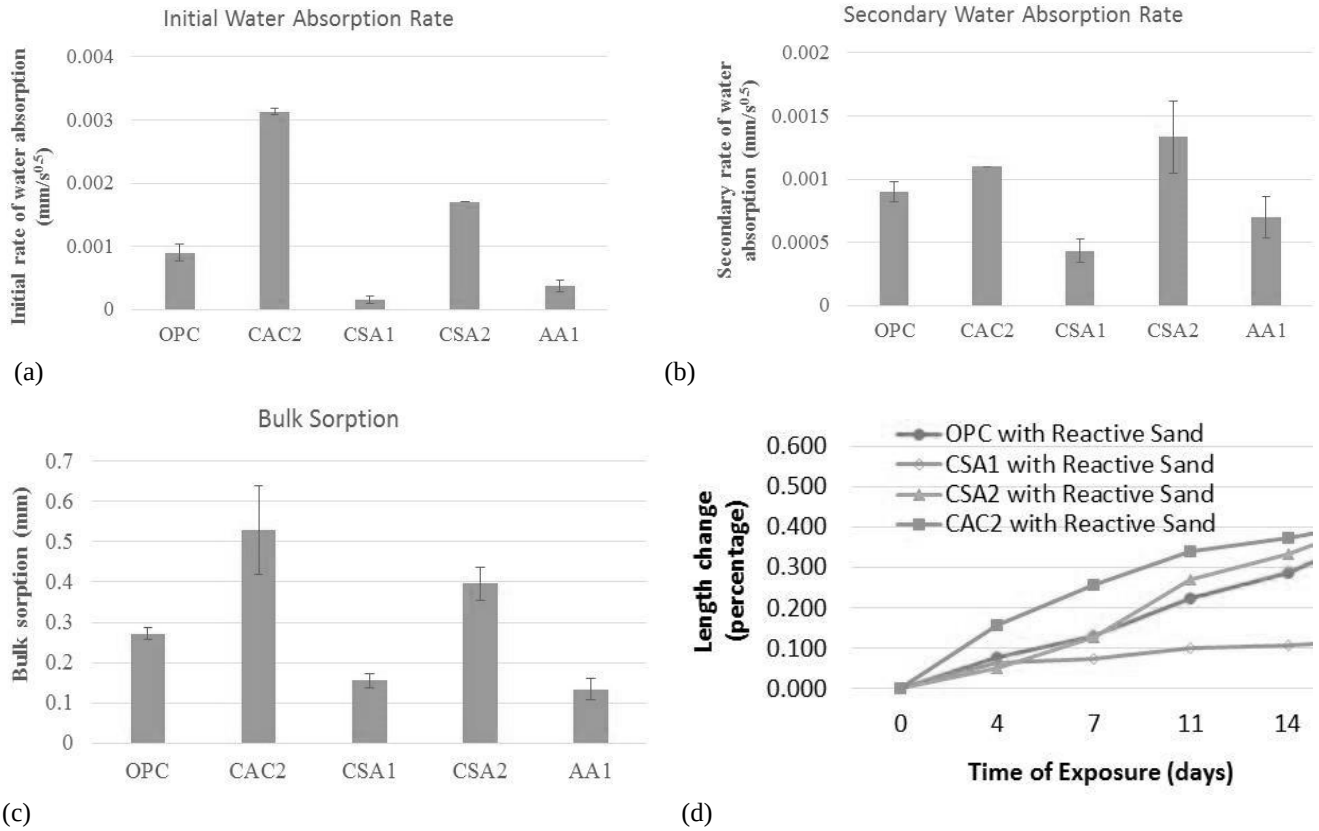

Figure 5. (a) Initial water absorption rate, (b) secondary water absorption rate (both by ASTM C1585), and (d) bulk sorption by ASTM C1757 on mortars cast at w/b=0.47, along with expansion results from accelerated mortar bar tests performed on portland cement and ACMs at same w/b and s/c with a reactive aggregate.

the appropriate w/b to establish FE with portland cement mortar based upon sorptivity. The approach demonstrated in Figure 5, where the standard mix proportions are used, but the sorptivity compared can be used to interpret existing data in a more meaningful way. It is not clear if the sorptivity data can be used more explicitly to normalize among data sets, but this avenue should be explored as well.

V. CONCLUDING REMARKS

While the shift over the prior decade from prescriptive to performance-based specification of binders facilitates to some extent the consideration of ACMs for larger scale concrete construction, significant challenges remain in "upscaling" ACMs from the laboratory scale to practical application in structural concrete. One of these is modernization of industry-accepted design guidelines, specifications, and codes [8]. In particular, adapting standards to provide guidance for accelerated durability testing that appropriately address ACMs is a critical step in smoothing the path for more rapid acceptance of emerging and next generation technologies in practice.

While the body of knowledge regarding field performance of ACMs continues to be developed, accelerated laboratory testing remains an important tool for growing understanding of ACM durability. Results from accelerated testing, performed appropriately where a functional equivalence has been established, can be useful for comparing among materials and designs.

This paper explored the significance of developing means to establish functional equivalence, allowing for streamlining in the adaptation of existing accelerated durability test methods. Some recommendations can be made:

- High range water reducing admixtures should be allowed to establish equivalent flow or slump, to an ordinary portland cement control, in standard testing for concrete.
- Water-to-cement or water-to-binder ratios by mass no longer serve to establish functional equivalence and the reliance on the use of these measures must be addressed to modernize current specifications.

- In accelerated test methods which rely upon interactions between a porous material and a surrounding aggressive environment, sorptivity may be a practical and appropriate method available for establishing functional equivalence between materials, enabling for more rapid and consistent asesssements of performance in the laboratory.
- Significant effort is needed to establish means for sorptivity testing in concretes and mortars which can be used to establish FE for a range of ACMs in a consistent way, without altering the structure or composition of the material.

Many ACMs offer benefits and improvements over traditional portland cements, including contributions to sustainability, but it remains challenging to gauge if their long-term performance meets expectations. Test methods and materials specifications must be updated to accommodate emerging and next-generation materials and technologies. In order to accomplish this it is necessary to have consistent and reliable methods by which to assess emerging materials.

Ultimately, if behavior and results from accelerated durability testing are be determined to be consistent with field performance, those data can be useful for developing appropriate performance criteria for specifications as well as predictive service life models.

VI. ACKNOWLEDGMENTS

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