Multi-Faceted Framework for Extrapolating Early Age Flexural Strength to Facilitate Rapid Lifting/Handling of High-Volume Fly Ash Precast Members

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ABSTRACT

Maintaining adequate early-age structural performance for precast concrete components has grown in importance as more sustainable mix designs become more widespread. Achieving high-early flexural strength is particularly crucial to facilitate rapid removal of hardened concrete components from formwork, often within twenty-four hours after fresh concrete placement. Limited research has assessed the effectiveness of traditional design methods in correlating flexural strength with compressive strength for next-generation mix designs, or demonstrated extrapolation of such material performance to larger-scale structural tests. This paper presents a multi-faceted framework to reassess early-age flexural strength for concretes made with relatively high proportions of fly ash from both fresh and harvested sources. The framework provides several pathways, from which the user can select based upon available resources and the specific application, to improve accuracy of early-age cracking moment calculations. Furthermore, the scope includes evaluation of strength performance under curing conditions emulative of those in a precast facility, recommending modulus of rupture equations which are more performance-driven than current design provisions, and experimental tests on prefabricated concrete beams to validate the proposed methodologies. Correlations of early-age strength with both concrete age and maturity measurements compare the effectiveness of utilizing in-situ data to further enhance the

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prediction methods. Ultimately, the proposed framework helped reduce errors when calculating cracking moment capacity at early ages by tailoring calculations to reflect mix-dependent behavior. Furthermore, most estimates of cracking moment were within 25% of their corresponding experimental test results, thus promoting confidence for using these strategies with high-volume fly ash precast structures.

Keywords: Precast, Fly Ash, Early-Age, Rupture, Cracking

1. INTRODUCTION

The use of supplementary cementitious materials (SCMs) in mix designs for prefabricated concrete components is becoming more widespread due to increasingly stringent restrictions for energy efficiency or carbon emissions during production of conventional Portland cement products. Fly ash has a longstanding history of beneficial use in concrete mixtures, however, due to is reduced heat of hydration, it can delay strength development, especially during the early-age window. Therefore, increased use of fly ash for concrete products like bricks [1], cast-in-place applications, or for nonstructural use [2] may have less barriers since the mechanical stresses experienced in these products during the fabrication phase are generally not substantial. Precast concrete components generally require rapid strength development during the initial fabrication and handling phase and thus traditionally have been the recipient of more strict limitations for fly ash use.

1.1. Motivation and Significance of Early-Age Flexural Strength for Precast

Development of high early flexural strength is of paramount importance during the fabrication of precast concrete components as this metric generally facilitates rapid removal of hardened concrete members from reusable formwork and thus helps optimize the efficiency of a precast facility. The design of many precast components calls for them to remain uncracked during lifting/handling and therefore the allowable flexural strength of the concrete must safely exceed the maximum tensile stress expected in the member at this stage, which often occurs within 24 hours after fresh concrete placement. The main design parameter used in the assessment of these objectives is the cracking moment (M_{cr}), which is computed as a function of the plain concrete modulus of rupture (f_r), the gross moment of inertia of the cross-section (I_g), and the distance from the neutral axis of the cross-section to extreme tension fiber (y_t), where cracking is expected to initiate. The mathematical expression for M_{cr} is shown in Equation 1 and f_r is calculated using a relationship with the corresponding compressive strength (f_{cm}), usually in accordance with ACI 318-19 [3] Equation 19.2.3.1 (see Equation 2 in this paper where strength units are in MPa and λ is a lightweight concrete factor taken as 1.0 for normalweight concrete for the purposes of this study), or via direct testing of unreinforced concrete beam specimens in accordance with ASTM C78 [4]. Since the former method relies on a fit equation based on the results of numerous experimental studies with varying types of concretes [5], it is generally recommended to reexamine the effectiveness of such an equation when new variations of mix formulations are evaluated. Furthermore, these conventional design equations were not developed specifically for the purpose of assessing the early-age performance of concretes with relatively high portland cement replacement fractions – as will be a major underlying focus of this study. Traditionally, incorporating larger fractions of fly ash in concrete mix designs results in lower heat of hydration of the binder matrix and consequently can delay the development of compressive or tensile strength of a hardened concrete specimen. Therefore, it is imperative to first demonstrate the scalability of the mechanical performance observed when testing high-volume fly ash (HVFA) concrete specimens up to larger-scale fabrication and testing of HVFA beams. Secondly, it is equally important to reassess the procedure for calculating early-age flexural strength to ensure the inherent mechanics of the novel mix designs are reflected in current design provisions or to recognize where modifications to such provisions may be needed in such cases moving forward.

$$M_{cr} = \frac{f_r \, I_g}{y_t} \qquad \text{Equation 1}$$

$$f_r = 0.623\lambda\sqrt{f_{cm}} \qquad \text{Equation 2}$$

In addition to its constituents, curing conditions – namely temperature and humidity – can significantly affect strength development of a given concrete mix, especially for applications where ambient conditions (i.e., uncontrolled temperature and humidity) are present during the curing process as is common in many precast facilities. Therefore, providing ambient conditions in the laboratory which emulate those expected under normal precast fabrication operations is critical to streamlining the scalability of the mechanical properties garnered from HVFA cylinders and small plain beams up to the corresponding performance of larger-sized HVFA beams or other types of precast components. Based on the aforementioned rationale, this paper presents a multi-faceted framework designed to streamline and customize the calculation of the early-age flexural strength of a structural concrete member fabricated with high-volume fly ash (including harvested or landfilled fly ashes) concretes. More specifically, the framework consists of three tracks, each with varying combinations of complexity and accuracy with respect to test results, that can be used to calculate the cracking moment. The first track is the most similar to conventional methods using a correlation between the modulus of rupture and the square root of the corresponding compressive strength, albeit with proposed modifications to the equation coefficients to more accurately capture the early-age behavior of novel HVFA mixes. The second track employs a maturity-based approach which correlates temperatures in HVFA concrete beams back to temperatures recorded during mechanical testing of small specimens (i.e., cylinders and small plain concrete beams) prepared with the same mix formulation to assist in generating strength development histories.

Lastly, the third track is based on direct modulus of rupture testing to calculate cracking moment and will largely be used for comparison with the other two tracks as it is theoretically the most straightforward and least reliant on statistical analyses – assuming the user has the proper equipment to perform this type of test. Several rounds of preliminary experimental testing of hardened HVFA concrete specimens under ambient curing conditions will influence slight modifications to conventional design equations for modulus of rupture as needed. Lastly, a series of larger-scale experimental tests on prefabricated HVFA concrete beams performed within 24 hours after fresh concrete placement will demonstrate the effectiveness of the proposed framework in estimating the cracking moment.

1.2. Influence of Concrete Maturity when Assessing Strength Development

Concrete maturity is defined as the area under the temperature-time history of a given concrete sample, ranging from the time of concrete placement to a given time of interest for estimating the strength of the mix. The maturity approach is commonly used to monitor the internal temperature of curing concrete and subsequently calculate the expected strength (e.g., compressive, flexural, etc.) by correlating the temperature reading back to a strength-maturation curve originally developed during mix trials in the laboratory. Noteworthy benefits of this approach are twofold, first is that the internal temperature of the member can be influenced by curing conditions and a relatively slow or faster curing regimen is more likely to be accounted for when estimating hardened concrete strength. Secondly, the use of maturity curves facilitates a non-destructive means of approximating in-situ concrete strength as it only requires a temperature sensor and does not necessitate costly or infeasible core samples to be extracted from the member as part of an in-situ evaluation.

A simple means to calculate concrete maturity, *M*, uses the Nurse-Saul function where the relationships between maturity and both age and temperature are assumed to be linear [6] as shown in Equation 3 where *t* is the age of the concrete (the time of placement is zero and the desired time at which to calculate maturity is t_f), *T* is the instantaneous temperature in the concrete, and T_0 is the datum temperature. Currently, there exist means of monitoring the maturity of in-situ concrete computationally with a remote temperature sensor and computer interface where mix proportions can be uploaded and maturity is determined based upon the Nurse-Saul method and current standards including ASTM C1074 [7], ASTM C918 [8], and ACI 318 [3]. Integrated calculation of maturity based on wireless continuous temperature monitoring streamlines maturity determination for novel mix designs, particularly those containing SCMs [9].

$$M = \sum_{t=0}^{t=t_f} (T - T_0) * \Delta t \qquad \text{Equation 3}$$

When originally proposed, concrete maturity was thought to manifest independent of curing conditions, but this hypothesis has since been disproven in literature [6,10–13]. It also does not account for the impact curing conditions have on the instantaneous temperature of the concrete (i.e. concrete cured outside, while generating the same amount of heat as concrete cured indoors, can lose significantly more heat to the ambient air). While instantaneous maturity can be considered independent of curing conditions, the rate at which maturity develops is heavily impacted by the surrounding curing environment. Although temperature fluctuations are often less of a concern for precast components fabricated under plant conditions (relative to cast-in-place construction), many precast facilities are not completely climate controlled and thus emulating the expected conditions in the factory is likely to produce the most accurate correlations between strength development and the maturity readings taken from a precast component when curing.

Geng et al. [6] found the Nurse-Saul method to be less accurate in environments where high temperature fluctuations are common, such as outdoors, and the relationship between recorded temperature and maturity may no longer be linear in such cases. Kanavaris and Soutsos [14] found that, in general, the Nurse-Saul equation will lead to a conservative estimate of strength, particularly at early ages and in the presence of heat curing. Their work resulted in a modified Nurse-Saul method to iteratively determine strength. Recognizing that maturity in the first 24 hours is often the most difficult to determine, Hrischev et al. [15] monitored temperature at two depths in their 50 x 50 x 25 cm concrete specimen and determined maturity using the Nurse-Saul method. Strength was tested at 1, 3, 7, 14, and 28 days, and determined as a logarithmic function of maturity. The calculated compressive strength was within 15% for concrete tested at 3 days and beyond, but their models were less accurate prior to 3 days [15], most likely because concrete curing conditions play a vital role in determining early age strength (and maturity). Kazemifard et al. [16] also determined compressive strength as a logarithmic function of maturity and, on average, their approach yielded 94% accuracy to compressive strength determined via destructive testing.

The equivalent age method was established for determining maturity in concrete cured in environments where temperature and maturity are not directly proportional (outside of 0-40ºC) and instead involves finding an equivalent age of the concrete based on an exponential function of the instantaneous internal temperature [9]. The maturity method outlined in ASTM C1074 [7] is well established for determining concrete age beyond 24 hours, and the framework herein follows a similar approach with an emphasis within the 24 hour age period. Literature supports a logarithmic relationship between maturity and strength [11,12,15–17] which commonly follows the format shown in Equation 4 where S is the strength (compressive, rupture, or other), M is the maturity of the concrete, determined manually pursuant to ASTM C1074 [7] or computationally using integrated software, X may be any base – but most commonly 10 or e – and a and b are mix-dependent constants, which are determined through destructive testing and regression analysis of the time- or maturity-dependent strength values.

$$S = a + b * \log_X M \qquad \text{Equation 4}$$

1.3. Influence of Curing Conditions

For the purposes of this study, temperature- and/or moisture-controlled curing environments will refer to the conditions found in a laboratory-type environmental chamber or other apparatus designed to allow concrete specimens to develop strength under ideal temperature and humidity. Contrarily, ambient curing will refer to open-air conditions of a laboratory setting or a precast facility, without close regulation of temperature and humidity. Heat produced during concrete curing (the result of the hydration of cementitious materials) does not develop as rapidly in temperature- and moisture-controlled environments, as is common in laboratory settings and curing chambers designed specifically to control these variables. Heat curing can also increase the rate at which maturity develops compared to both temperature- and moisture-controlled curing (i.e. curing chambers) and ambient curing. In extreme weather conditions, maturity has been shown to be a better indicator of early-age strength than time [12]. Tekle et al. [12] also found that the effect of extreme cold environments on compressive strength development is not solely proportional to the maturity parameter. At the same maturity, concrete cured in cold weather environments achieved lower strength than concrete cured in more temperate environments, further enforcing the conclusion that the Nurse-Saul method is not accurate for nonlinear (irregular) maturity development. This concept generally applies to a range of curing environments; for example, it can be expected that concrete cured in heated environments will achieve higher early-age strengths than conventionally cured (ambient or temperature- and moisture-controlled) concrete at the same maturity.

Ambient curing conditions, like those of cast-in-place or some large-scale precast facilities, mean that the instantaneous temperature in the concrete is subject to fluctuations that will inevitably occur over the curing cycle. Certain curing environments can maintain specific temperatures and/or moisture levels to ensure optimal curing conditions in closed environments, such as in environmental chambers. Temperature and humidity chambers ensure that the curing environment remains consistent, or otherwise controlled over time. Maintaining consistent temperature conditions yields slowed maturity development, which may lead to delayed strength development as this is linked to the curing process. Curing chambers also help to ensure the relationship between temperature and maturity remains linear by limiting temperature fluctuations [6]. Better approximations of maturity and the corresponding strength performance allow for more informed timing of strength-dependent construction processes [13]. Idealized conditions, like those present in a curing chamber, are not guaranteed in most batching scenarios, and the repeatability of ideal conditions should not be assumed. Thus, it is important to know the direct impacts of curing temperature on maturity (and analogously, strength) development. Under the scope of this research, maturity under ambient curing conditions was observed, and the corresponding strength was recorded as a function of maturity between concrete ages of 12 and 24 hours. In general, it was found that under ideal curing conditions, notably 23ºC (73.4°F), 95% humidity in the context of concrete specimens [18], maturity develops proportionality to curing environment temperature whereas in ambient warm weather conditions (particularly, 25ºC (77ºF), 50% humidity as found in the lab set up for testing purposes in this research), maturity development was more accelerated relative to the ambient temperature.

2. STRENGTH DEVELOPMENT BEHAVIOR

A critical preliminary step in advance of deploying the framework is to assess the early-age strength development behavior of a given HVFA mix design in the relevant environment of its intended application. Previous research by the authors [19] presented a methodology to characterize the early-age strength development of novel HVFA mixes, albeit under temperature- and humidity-controlled curing conditions in an environmental chamber. To increase the effectiveness of that procedure for the purposes of calculating the early-age flexural capacity of a precast component, this paper presents two extensions of that original work. The first subjects the novel HVFA concretes to a curing environment that emulates the ambient conditions generally found in a precast facility to facilitate more accurate flexural strength prediction under the influence of the relevant temperature and humidity. The second adds concrete maturity as an auxiliary baseline, in addition to concrete age, for which to characterize concrete compressive and flexural strength against. Generally, time-based methods are recommended when curing conditions will not vary between batches (like indoors, or in temperature- and humidity- controlled environments) whereas the maturity-based approach may be better suited for curing environments where temperature and humidity may vary between batches (such as outdoors). To generate strength development curves to reflect these two objectives, a series of additional experimental tests were conducted using the best performing HVFA mix design from each group of fresh Class C (*C40-G-NCA*), fresh Class F (*F40-SHA*), and a harvested Class F fly ash (*L40-G-CI*) as documented in Ordillas et al. [19]. During this study, compressive testing pursuant to ASTM C39 [20] and subsequent characterization of compressive strength relative to time or maturity was conducted within 24 hours of fresh concrete batching and specimen preparation. From plots of time-dependent strength, a straightforward regression analysis was used to obtain a logarithmic relationship for compressive strength as a function of concrete age, *t*, as show in Equation 5 pursuant to supporting literature [11,12,15–17] where a and b are mix-dependent constants.

$$f_{cm} = a + b * \log_{10} t \qquad \text{Equation 5}$$

These constants will change for a given mix and care should be taken to maintain curing conditions during subsequent concrete production to ensure the best estimate of time-dependent strength. Using time as the independent variable simplifies determination of strength when compared to ASTM C1074 [7] if it is not feasible to monitor maturity for a given concrete member. For each fly ash type (Class C, Class F, and harvested), compressive strength was determined pursuant to ASTM C39 [20] and modulus of rupture was assessed in accordance with ASTM C78 [4] at ages of 12, 16, 20, and 24 hours. Maturity was also recorded at the time of each specimen test using a wireless temperature sensor placed in an extra concrete cylinder. Compressive and rupture strength data were then compiled, and these values were then used to determine an overall HVFA strength approximation equation with respect to time and maturity, as well as mix-dependent equations for each different fly ash type. Figure 1 presents compressive strength as a function of concrete age, Figure 2 shows compressive strength as a function of concrete maturity, and Figure 3 shows modulus of rupture as a function of compressive strength. The corresponding fit equations (taking the form shown in Equation 5) for Figure 1, 2, and 3 are Equation 6-9, 10-13, and 14-17, respectively, where the unit of strength is MPa, time is in hours, and maturity is in °C-hrs (note that λ was taken as 1.0 in every case due to the uniform use of normalweight concrete). Although the behavior of each HVFA mix design was assessed separately, general equations (see Equation 9, 13 and 17) were also proposed as average fitting functions across the three separate 40% HVFA mixes examined in this study. Please note that the calculated compressive strength must be greater than or equal to zero at any given age since the fitting equations herein were adjusted to capture the best form of the data considering the effect of concrete setting time which manifests as an offset to when significant strength development commences.

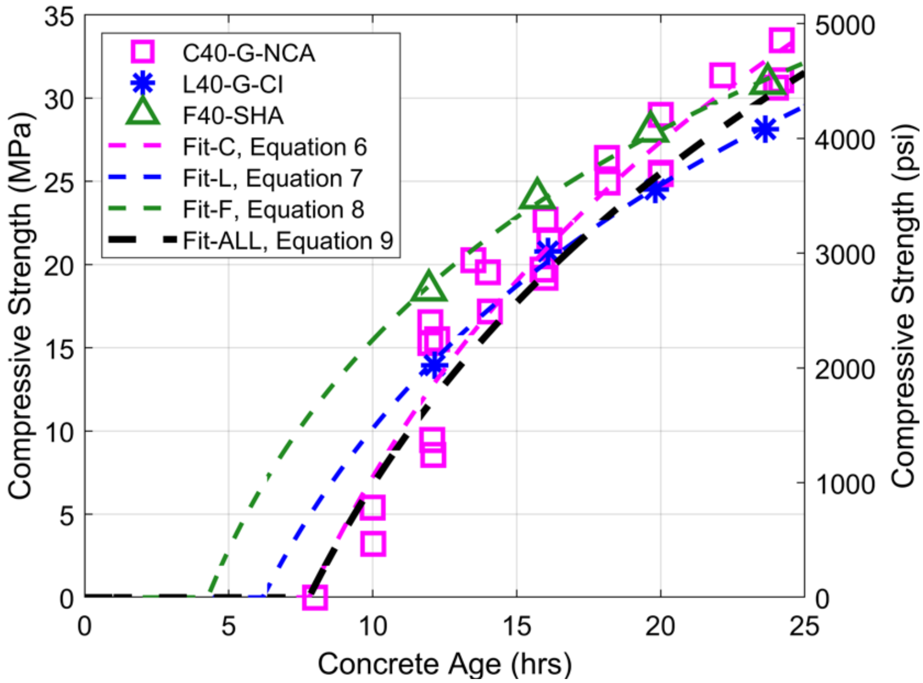

Figure 1 – Early-age compressive strength versus concrete age for HVFA mix designs

$$f_{cm} = \max(66.88 \log t - 59.64, 0)$$ Equation 6

$$f_{cm} = \max(48.66 \log t - 38.51, 0)$$ Equation 7

$$f_{cm} = \max(41.86 \log t - 26.39, 0)$$ Equation 8

$$f_{cm} = \max(62.22 \log t - 55.46, 0)$$ Equation 9

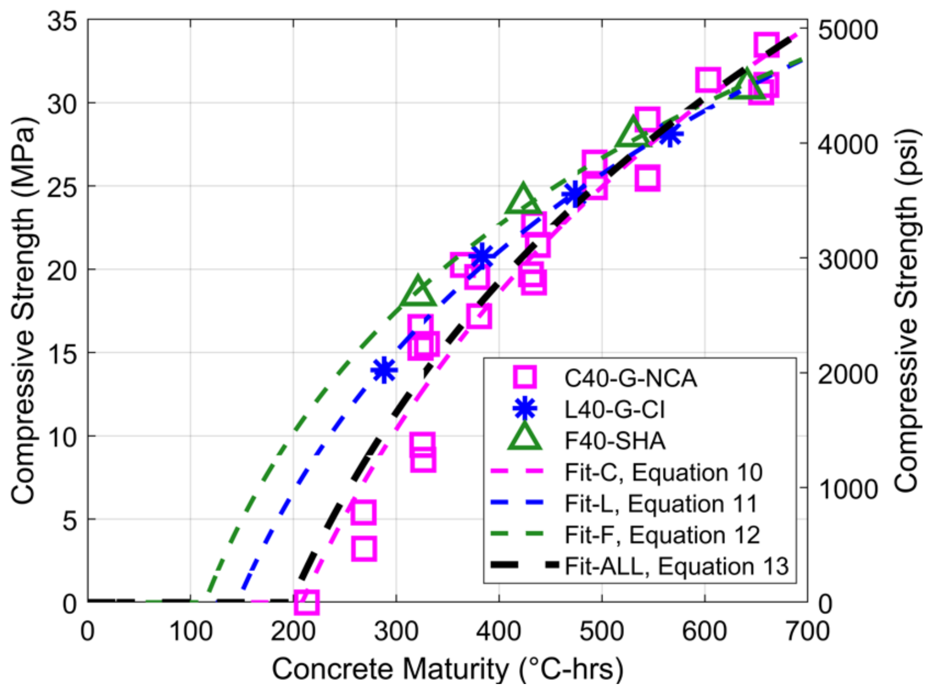

Figure 2 – Early-age compressive strength versus concrete maturity for HVFA mix designs

$$f_{cm} = \max(9524 \log M - 22086, 0)$$ Equation 10

$$f_{cm} = \max(6958 \log M - 15049, 0)$$ Equation 11

$$f_{cm} = \max(6022 \log M - 12383, 0)$$ Equation 12

$$f_{cm} = \max(9107 \log M - 20907, 0)$$ Equation 13

While Equation 2 is generally conservative for the mix formulations shown in Figure 3, developing more performance-driven equations to represent modulus of rupture can further optimize precast casting bed turnover as the behavior (with respect to the standard design equation) may be deemed overly conservative for certain applications.

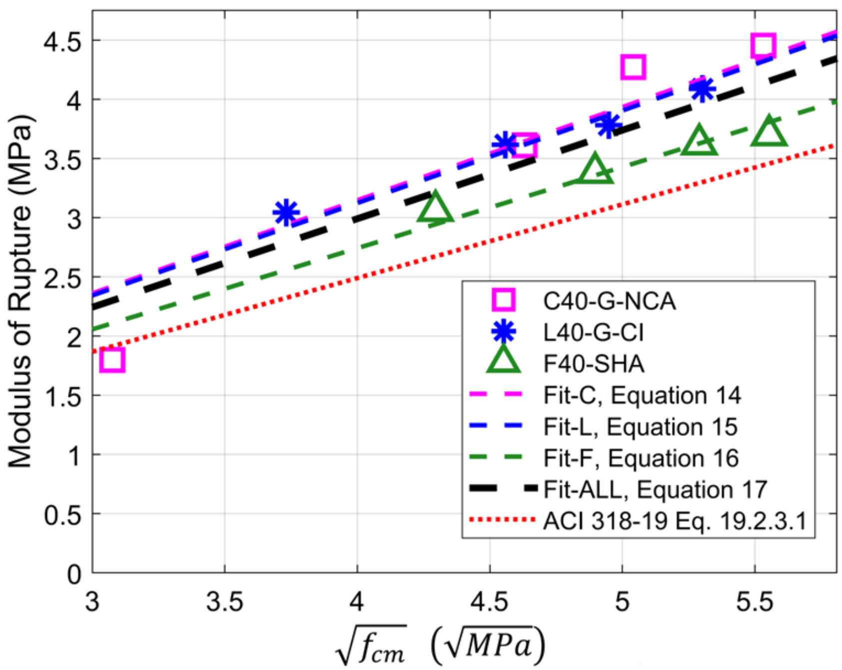

Figure 3 – Characterization of early-age modulus of rupture test results as a function of the corresponding compressive strength results

$$f_r = 0.787\sqrt{f_{cm}} \qquad \text{Equation 14}$$

$$f_r = 0.781\sqrt{f_{cm}} \qquad \text{Equation 15}$$

$$f_r = 0.686\sqrt{f_{cm}} \qquad \text{Equation 16}$$

$$f_r = 0.748\sqrt{f_{cm}} \qquad \text{Equation 17}$$

3. PROPOSED EARLY-AGE CRACKING MOMENT FRAMEWORK

The proposed framework aims to provide a thorough means of optimizing cracking moment approximations pursuant to the capabilities of the user; Thread I provides an estimate of strength based upon concrete age and can be used in environments where curing conditions generally do not fluctuate between batches, or if means of determining maturity are not feasible. This estimate can be taken as an improvement relative to the currently accepted means of determining strength as Thread I accounts for mix-specific strength development rather than an average of historical concrete strength values. Thread II provides the advantage of accounting for the impact curing environment (namely temperature and humidity) has on strength development. This estimate is recommended in environments where curing conditions are expected to vary significantly between batches, and is expected to provide a more informed estimate of strength development than Thread I. Threads I and II have the benefit of requiring compressive testing of cylinders without any additional flexural testing or specimen batching, should this be a consideration at the discretion of the user. Thread III provides a more direct estimate of cracking moment based upon age-dependent flexural strength obtained from testing pursuant to ASTM C78 [4]. This particular approach requires less statistical analyses, but necessitates casting of unreinforced flexural beams and the utilization of 4-point flexural testing for determination of f_r rather than calculation from the relationship between f_{cm} and f_r as described in Equation 14-Equation 17.

For the purposes of the framework presented herein, compressive strength development can first be characterized as a function of time or maturity. Thus, upon establishing an approximate strength curve, it is then possible to determine the age or maturity at which a given concrete mix achieves a target strength, or another specified performance metric. Using predefined strength gain history curves which allow the user to approximate the instantaneous compressive or flexural strength will likely minimize the extent of mechanical testing of hardened concrete specimens during the early-age period. Once the user interpolates the age at which the target concrete strength is expected to manifest, destructive mechanical testing of cylinders and/or plain concrete beams can then serve to verify the strength performance as opposed to relying on multiple laboratory tests throughout the anticipated early-age window. This information can then facilitate removal of hardened HVFA components from formwork and more broadly contribute to optimizing turnover of casting beds. Moreover, the outcomes of this approach will help to streamline the process for informed estimation of elastic region concrete behavior at critical points like lifting/handling, and supports integration of higher replacement values of SCMs in precast applications with stringent early-age strength requirements. All approaches herein provide an approximation for concrete cracking moment within the 24 hour early-age window, which is generally the most critical time period for precast facilities as discussed previously.

Figure 4 presents a graphical description of the proposed framework and the three threads, each with varying fidelity and complexity from which the user can choose to estimate the early-age cracking moment. The framework was originally developed in a laboratory where ambient conditions and basic equipment emulative those found in a precast facility. Therefore, the steps outlined in Figure 4 can also be applied in a realistic precast environment where access to relevant testing resources and equipment is also available. The process of extrapolating material properties for use with larger-scale precast component is fairly standard, however, the novel pathways and their associated design recommends are meant to further enhance precast productivity without neglecting pertinent structural limit states in the early-age window. Thread I utilizes an age-dependent procedure, whereas Thread II incorporates maturity measurements to account for the internal temperature of the concrete. Thread III relies on direct testing of modulus of rupture, if feasible for the user. The three main rows provide the critical steps needed to calculate the cracking moment for each thread. These steps first include correlating compressive strength to time or maturity, then calculating modulus of rupture from relationships with the corresponding compressive strength or direct testing, and finally calculating the cracking moment of a concrete section with the obtained modulus of rupture. The main advantage of using this framework comes from allowing the user to select the best thread for a given application, the resources available (e.g., testing equipment, maturity sensors, etc.), and the intended fabrication and curing conditions. Thread I is likely the simplest to implement as it does not require maturity sensors and is the most familiar with standard practice of calculating the cracking moment. Thread II is likely more advantageous with variable curing conditions or when maturity sensors are already being used on a given job to track strength development. Thread III is the most straightforward but will likely require more laboratory work as it lacks a correlation with time or maturity to approximate strength rather than performing multiple rounds of testing on plain concrete beam samples. Towards the end of this paper, the accuracy of each thread will be demonstrated in conjunction with experimental test results for HVFA concrete beams and the outcomes will provide additional insight when choosing which thread to use for a given case. It should be noted that the experimental validation step (i.e., the fourth row as shown in Figure 4) will likely not be feasible for the user and was added in this study to demonstrate the effectiveness of the proposed framework. Large-scale structural testing conducted to fulfill the optional fourth row in the framework (see Figure 4) can be to provide validation of the three pathways for the user with their specific types of components or applications. A case study will provide an example test program to provide data for the purposes of this fourth row will be presented in Section 3.4 of this paper.

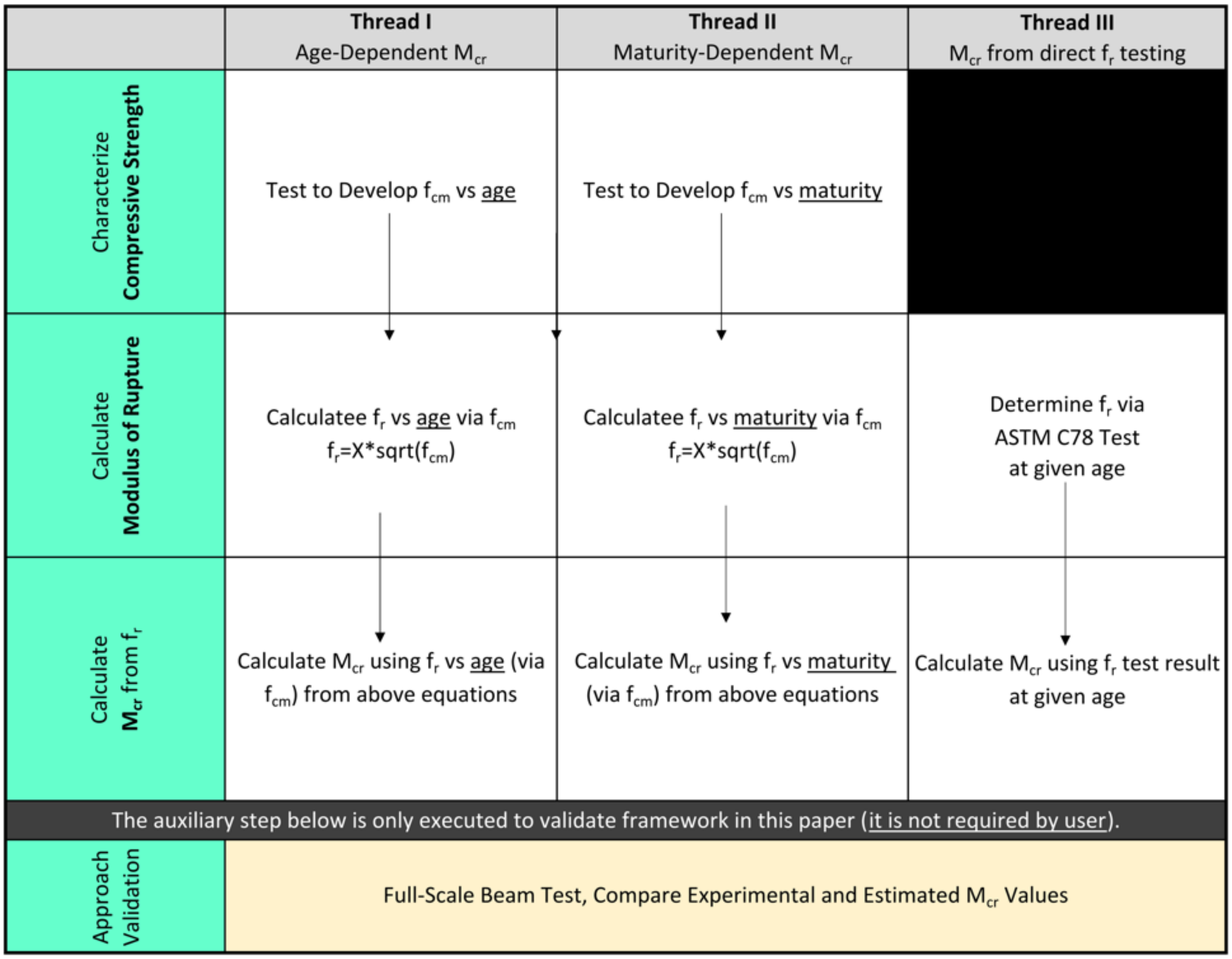

Figure 4 – Flowchart showing proposed multi-dimensional cracking moment calculation framework

3.1. Thread I: Cracking Moment via Age-Dependent Strength

The results outlined in this thread were used to determine compressive, and ultimately flexural strength, with respect to concrete age. The steps outlined in Section 2 to produce the compressive strength versus concrete age relationship, like the examples done for this paper shown in Figure 1, should first be followed. Laboratory modulus of rupture tests done at the same age as the cylinder tests will then facilitate correlations with the square root of the corresponding compressive strength, as was done in Figure 3 and Equation 14-Equation 17 for demonstration purposes in this paper. Thread I also provides the option to bypass modulus of rupture testing (if equipment is not available for example) and instead use Equation 2 to calculate it from compressive strength (with expectedly less accuracy). The cracking moment capacity can then be calculated using Equation 1 which will indirectly correlate it back to concrete age. The user can then determine the concrete age (via back-calculation in the relationship plot) at which the estimated cracking moment capacity exceeds the maximum moment demand expected during lifting of the component to ensure the member remains uncracked (especially for Class U prestressed members). The user may elect to impose a safety margin to ensure the cracking moment capacity remains comfortably higher than the corresponding moment demand. Select precast and/or prestressed members may necessitate stress checks during lifting and handling and in such applications, comparisons between modulus of rupture calculated using Thread I or Thread II (see below) and the tensile stress demand may substitute for the cracking moment check.

3.2. Thread II: Cracking Moment via Maturity-Dependent Strength

Similar to Thread I (see Section 3.1) with the exception of now using temperature sensors, the steps outlined in Section 2 should be followed to construct the compressive strength versus concrete maturity relationship, like in the examples done for this paper as shown in Figure 2. The approach to calculate modulus of rupture and subsequently the cracking moment for a given section is then the same as discussed in Thread I. The maturity corresponding to the desired cracking moment capacity can then be back-calculated to arrive at the target maturity value to commence lifting/handling. That target value can then be checked against the data acquired from a wireless temperature sensor (the same one used to determine the concrete maturity values during preliminary testing should be used to eliminate any sources of error between sensor models) installed in the member and activated prior to concrete placement in the precast plant.

3.3. Thread III: Cracking Moment via Direct Modulus of Rupture Testing

The third thread likely will facilitate the most straightforward prediction of the cracking moment as it relies on direct modulus of rupture testing (in accordance with ASTM C78 [4]) to commence lifting/handling. It may, however, be more difficult to implement unless the laboratory at a given precast facility has the equipment and complementary instrumentation needed to perform the test. If this option is selected, it is important that plain concrete beams for modulus of rupture testing be subjected to a curing environment that emulates the conditions exposed to the precast member in the casting beds. For the purposes of this study, this third thread will largely serve as an auxiliary comparison to the first two threads due to its independence of relationships between modulus of rupture and the corresponding compressive strength.

3.4. Validation with Experimental Beam Test Data

In order to validate the streamlined framework proposed herein for estimating early-age cracking moment capacity, a half-scale inverted tee section with dimensions as shown in Figure 5 (reference section is 28IT20 from the PCI Design Handbook [21]) with an overall length of 3.35 m (11 ft.) was cast from each fly ash mix examined for age- and maturity-dependent strength development (i.e., *C40-G-NCA*, *F40-SHA*, and *L40-G-CI* as presented in Ordillas et al. [19]). The members were loaded in three-point bending with simple supports and a span length of 3.1 m (10 ft.) using a large-format universal testing machine – a photo showing the complete test setup is shown in Figure 6. During the test, the crosshead, to which a steel roller was mounted to simulate a point load, is locked while the bottom platform, on which the two supports rest, is raised using an automatic displacement-controlled profile. Force was recorded using a pancake load cell bolted directly above the center steel roller and midspan deflection was acquired using a string potentiometer mounted to the test frame below the beam.

The age and maturity of the concrete was recorded at the onset of each test, and the applied moment at which cracking occurred was compared to the predicted cracking moment of the section using the three threads presented in Sections 3.1 through 3.3. Table 1 provides the age and corresponding maturity of the concrete for each beam test, which were selected such that the expected cracking moment exceeded the maximum lifting/handling induced (i.e., self-weight) moment by a factor of at least 6. This decision was made to ensure premature cracking did not occur during lifting/handling, since the members were prefabricated in the lab, and consequently compromise the safety of the researchers. Additionally, realistic precast members with relatively larger span to depth ratios will crack at significantly less applied force for a given modulus of rupture which justifies using a higher factor in the testing program. Note that the maturity values recorded in Table 1 were obtained at the time of the test from wireless temperature sensors with a probe embedded in the beams. Table 1 also shows the average experimental modulus of rupture at the time of each beam test which is needed for Thread III of the framework.

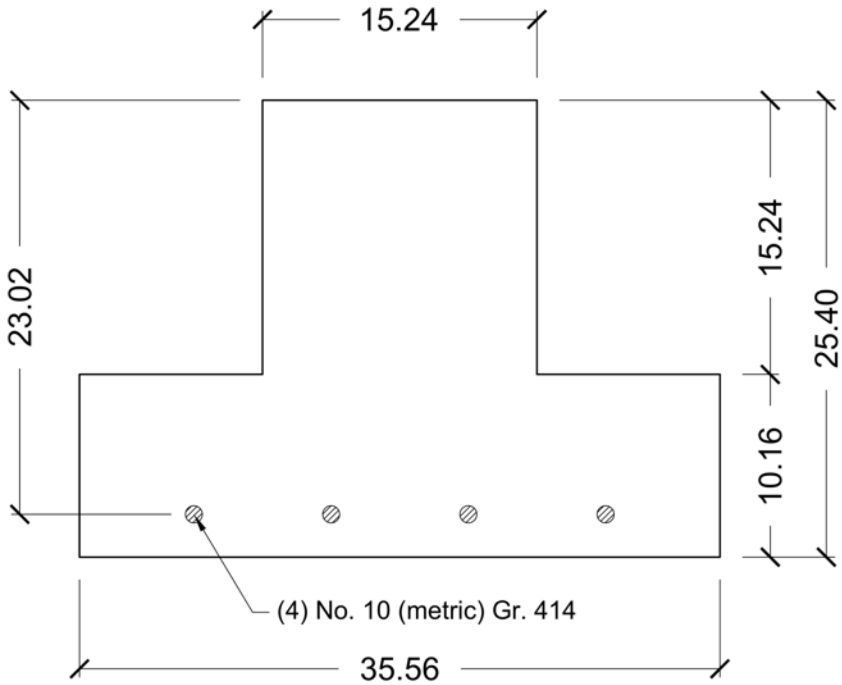

Figure 5 – Inverted tee beam cross-section used in experimental tests (length dimensions in cm)

Figure 6 – Photo of an experimental HVFA inverted tee beam installed in the test setup

Table 1 – Average mechanical testing results and timeframes corresponding to beam tests

Beam ID	Mix ID (see Ordillas et al [19])	Age at Test (hrs)	Maturity at Test (°C-hrs)	f_r (MPa)
C	*C40-G-NCA*	17	358	3.61
L	*L40-G-CI*	16.5	507	3.95
F	*F40-SHA*	16.75	528	3.85

Figure 7-9 present plots of applied moment versus midspan deflection derived from experimental test data for beams C, L, and F, respectively. Also plotted in these three figures are the estimated cracking moment values as tabulated in Table 2 which were obtained using the three threads of the framework proposed in Sections 3.1 through 3.3. For Threads I (*T1*) and II (*T2*), two values were calculated – one using the average (*AVG*) fit equations across all fly ash types (see Equation 9, 13, and 17) and the other using the mix-specific (*MIX*) equation (see Equation 6-8, 10-12, and 14-16). Note that the *Experimental* M_{cr} value from each test was approximated graphically as the point where the *Test Data* curve first deviated from its linear-elastic region (i.e., the approximate proportional limit) via monitoring of the tangent stiffness. Figures 7-9 show that the cracking moment capacity estimates are conservative with respect to the corresponding experimental test result for each of the three beams, albeit less conservative than using Equation 2 to calculate the modulus of rupture since its coefficient (i.e., 0.623) is less than those of Equation 14-17 used to develop these figures. Therefore, while Equation 2 may facilitate a more conservative design, the implementation of Equation 14-17 will facilitate more accurate, performance-driven estimates of early-age cracking moment performance with beneficial applications for the fabrication of precast components. Furthermore, even with the higher coefficients proposed to calculate modulus of rupture, a comfortable margin of safety remains between the estimated cracking moment values and the actual results determined from experimental testing. This observation may help to overcome some reservations about using a less conservative, performance-driven equation in place of the more established Equation 2. As for assessing the relative effectiveness of the three framework threads, Table 2 highlights that the majority of cases exhibited error percentage magnitudes of 25% or less. Thread III (*T3*), developed to be the most straightforward comparison between modulus of rupture and cracking moment, did not produce the most accurate result for any of the three beam cases. Generally, the age-dependent approaches performed well for beam C and the maturity-dependent calculations demonstrated the best performance for beams L and F. These results reinforce the importance of thoroughly evaluating a given mix design while scaling up its use for precast structural components and motivates the use of the framework developed herein to facilitate more accurate and comprehensive assessments of early-age cracking moment performance.

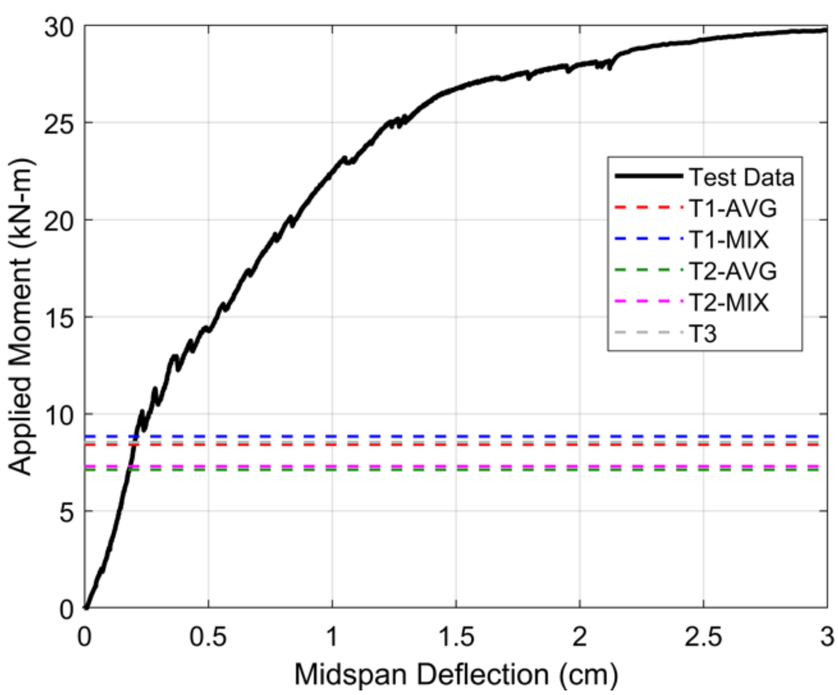

Figure 7 – Experimental moment versus midspan deflection results for beam C along with estimated cracking moment values

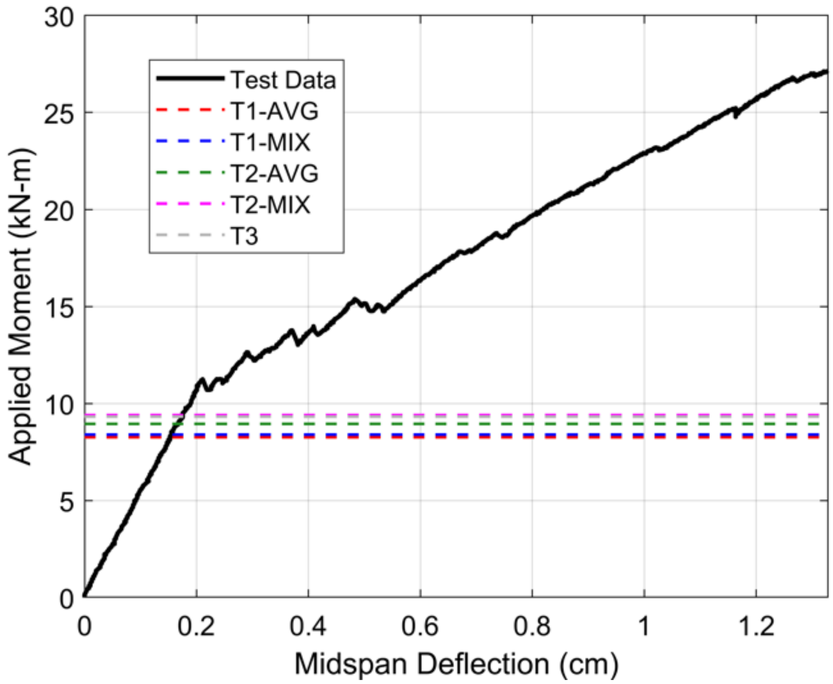

Figure 8 – Experimental moment versus midspan deflection results for beam L along with estimated cracking moment values

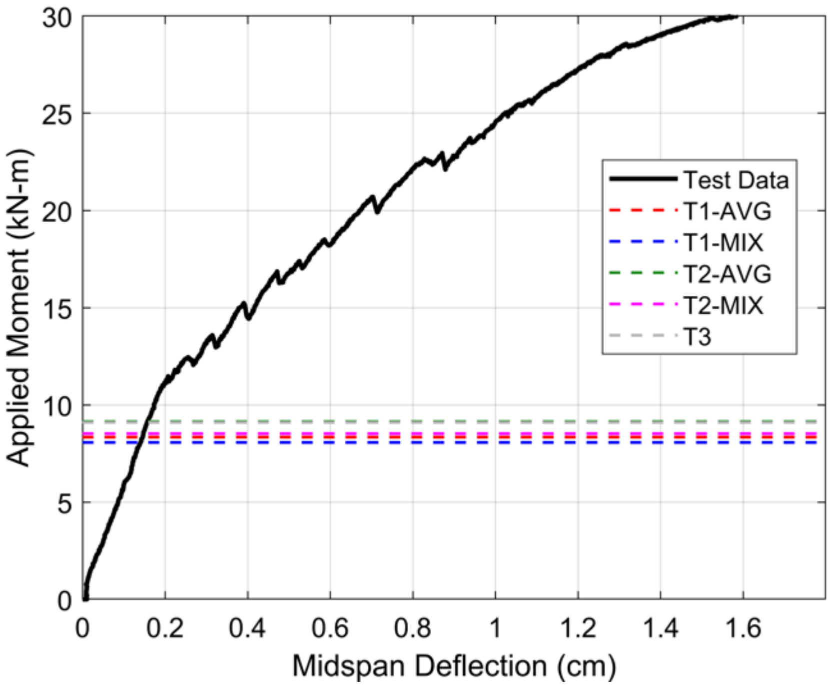

Figure 9 – Experimental moment versus midspan deflection results for beam F along with estimated cracking moment values

Table 2 – Estimates of cracking moment capacity for each beam using the three framework threads

Beam ID	C	L	F
Experimental M_{cr} [kN-m]	10.13	11.22	11.15
Average Fit Thread I M_{cr} [kN-m]*	8.42 (-16.9 %)	8.26 (-26.4 %)	8.34 (-25.2 %)
Mix Fit Thread I M_{cr} [kN-m]*	8.84 (-12.8 %)	8.39 (-25.2 %)	8.07 (-27.7 %)
Average Fit Thread II M_{cr} [kN-m]*	7.12 (-29.8 %)	8.95 (-20.2 %)	9.14 (-18.0 %)
Mix Fit Thread II M_{cr} [kN-m]*	7.30 (-28.0 %)	9.40 (-16.2 %)	8.52 (-23.6 %)
Thread III M_{cr} [kN-m]*	8.53 (-15.8 %)	9.32 (-16.9 %)	9.10 (-18.4 %)

*<u>Note</u>: Error % relative to *Experimental* M_{cr} value is show in parentheses in subsequent rows.

4. SUMMARY AND CONCLUSIONS

This paper proposed a multi-faceted framework structured to improve the accuracy of calculating early-age flexural strength of precast components fabricated using high-volume fly ash concrete mixes. The framework contains three threads (or options) from which the user can select depending on the application or resources available to them. The first thread estimates the cracking moment of a structural concrete beam simply as a function of the age of the concrete whereas the second thread relies on measurements of concrete maturity as a more sophisticated indicator of concrete strength development. Lastly, the third thread is theoretically the most straightforward as it relies on direct modulus of rupture testing at the time when cracking moment is to be calculated, rather than using a strength gain model. Traditional correlations between modulus of rupture and the square root of the corresponding compressive strength have been reassessed for high early strength concretes with high fractions of Portland cement replacement with fly ash. Additionally, this performance was evaluated under the influence of ambient curing conditions which emulate the environment of a typical precast facility. A series of experimental tests on concrete beams prefabricated in a laboratory setting emulative of a precast facility helped to further demonstrate scalability of the HVFA mix designs used in this study and also served to produce data for validation of the proposed framework. More specifically, the following primary conclusions can be drawn based on the research performed in this study:

- Straightforward log-based equations were proposed to approximate early-age compressive strength as a function of concrete age or maturity, from which modulus of rupture can then be calculated. Using compressive strength as the starting point for Threads I and II aims to facilitate ease of implementation for these approaches as cylinder tests are typically most convenient and straightforward to run in the materials laboratory at a precast facility.

- The proposed framework leads to improved accuracy when calculating the modulus of rupture as a function of the square root of the compressive strength. Whereas ACI 318-19 Equation 19.2.3.1 uses a coefficient of 0.623, the values determined in this study range from 0.686 to 0.787. Experimental tests of prefabricated concrete beams showed the new coefficients still facilitate safe estimates of cracking moment despite their inherently less conservative nature.
- Estimates of cracking moment were within 25% of their corresponding experimental test result in the majority of cases examined in this paper. While arguably the most straightforward approach, Thread III was not the most accurate method with any of the three beam tests.
- The concrete age-based Thread I was most accurate for the fresh Class C fly ash beam, coming within 12.8% of the experimental cracking moment in that case. The maturity-based Thread II was most accurate for the landfilled and fresh Class F fly ash beams, with error percentages of 16.2% and 18.0%, respectively.
- Average fitting equations developed using the total breadth of data for all three fly ash types were generally less accurate, relative to those proposed for each fly ash type separately, in estimating cracking moment, except for the fresh Class F fly ash beam.

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