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Charpy Impact Test Methods for Cementitious Composites: Review and Commentary

Reference

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ABSTRACT

Several researchers have recently employed the Charpy method to characterize the high strain rate mechanical strength of cementitious composites. This paper provides a critical review of existing applications of the Charpy method for impact testing of cementitious composites. Studies have employed various specimen sizes and geometries. Additionally, some studies have tested notched specimens while others have tested plain. Furthermore, varying methods of normalization result in results reported in a variety of incompatible units. The lack of consistency between studies limits the basis for comparison and the ability to validate results, which demonstrates a clear need for a standardized method for Charpy impact testing of cementitious composites. The authors recommend best practices based on sound mechanical principles and existing literature. Finally, the benefits and drawbacks of the Charpy method are discussed and its efficacy is compared with other prevalent methods for impact testing of cementitious composites.

Keywords

Charpy impact test, cement, concrete, mortar, cementitious composites, impact strength

Introduction

The mechanical response of cementitious composites is strain rate dependent. The dynamic strength exceeds the quasistatic strength by a stout margin at high strain rates [1–6]. The strain rate dependence of concrete was first noted by Abrams [1] in 1917 and later corroborated by Jones and Richart [7] in 1936, Watstein [8] in 1953, and Atchley and Furr [9] in 1967. The strength improvement at high strain rates is typically expressed as the dynamic increase factor, $DIF = f_d/f_s$, where f_d is the dynamic strength and f_s is the quasistatic strength. The dynamic increase factor is sensitive to the dynamic strain rate and the quasistatic compressive strength [5,6,10]. Several empirical models of the dynamic increase factor for the compressive strength, tensile strength, and other mechanical properties of concrete are in common use [10–14]. The development of advanced cementitious composites requires continual experimental efforts to characterize the dynamic mechanical response of these novel materials.

Test methods for the dynamic mechanical properties of materials rely on principles of potential energy, kinetic energy, or stress wave propagation [15]. Often called true impact methods, those based on kinetic energy (e.g., projectile impact) provide the most realistic impact scenarios. However, the challenges associated with acquiring quantitative response data during such high intensity loadings are often prohibitive. Test methods based on the principles of stress wave propagation (e.g., Kolsky bar [16,17]) use the theory of wave propagation through elastic solids [18,19] to infer the mechanical response of materials under high intensity loadings, but the physical size of the apparatus required for testing of cementitious composites is unrealistic [15]. As a result, potential energy test methods (e.g., drop-weight [20,21] and pendulum [22–24]) are generally favored for impact testing of cementitious composites.

The drop-weight impact test [20,21] has gained particular favor within the concrete community. A variant of this test has been standardized for use with fiber reinforced concrete by ACI Committee 544 [25], which involves repeatedly dropping a 44.7 N hammer from a distance of 0.457 m onto the flat face of a cylindrical specimen. A hardened steel ball is used to transfer the impact force from the hammer to the specimen, and the number of blows required to initiate ultimate fracture is takes as an indication of the impact resistance. The test is often criticized for its high variability [25] but has nonetheless been frequently employed for impact testing of fiber reinforced concrete and other cementitious composites.

The Charpy impact test, which makes use of the potential energy of a falling pendulum to fracture specimens at high strain rates, has also been frequently employed for characterization of cementitious composites. Demonstrated by Russell [22] and Charpy [23] near the turn of the 20th century and standardized by the American Society of Testing and Materials in 1933 [26], the Charpy test has long been used to characterize the ductile-brittle transition of metallic materials at varying temperature [27,28]. The impact energy absorbed during dynamic fracture is evaluated by the loss in potential energy of the falling weighted pendulum. The Izod test [24], which is identical to the Charpy test except that the specimen is cantilevered, has also been used for impact testing of materials. The cantilevered test configuration requires that specimens be vise mounted. The resulting biaxial stress state reduces the apparent strength [29]. Thus, for the same reason that direct tensile tests of cementitious composites are problematic [30], the Izod test can be categorically disqualified for use with cementitious composites.

Despite a number of studies that have reported Charpy impact test results for cementitious composites, there is no accepted standard for such tests. Standardized methods do exist for Charpy testing of metals [31,32] and plastics [33,34], and the same apparatus are used for Charpy testing of cementitious composites. These standards are in many ways poorly applicable to impact testing of aggregative materials, and so authors are left to adapt existing standards as they see fit. The absence of a standardized method for Charpy testing of cementitious composites has led to a lack of consistency in experimental parameters and has limited the basis for comparison of results between similar studies. This paper reviews the experimental details (e.g., specimen size, aspect ratio, notch provision, data normalization) of more than 20 studies that report Charpy impact test results for cementitious composites. Commentary on these topics is provided based on sound mechanical principles in the hopes that this discussion will prove useful in the development of a standardized test method for Charpy impact testing of cementitious composites.

The Charpy Test

The Charpy impact test relies on the potential energy of a weighted pendulum as shown in **Fig. 1**. The pendulum is raised to some initial height h_i, which is measured from the center of mass to the datum. The initial potential energy $E_i = mgh_i$, where m is the pendulum mass and g is the acceleration due to gravity. A simply supported prismatic specimen is held in a support anvil at the bottom of the arc path of the hammer. Upon release of the pendulum, the hammer strikes the specimen at midspan as shown in **Fig. 2**. The specimen fractures, and the pendulum continues through its arc to some final height h_f, also measured from the center of mass to the datum. The remaining potential energy is $E_f = mgh_f$. The difference $E = E_i - E_f$, corrected for losses due to friction and drag, is the energy absorbed by the specimen during fracture. Neglecting losses due to friction and drag, the approximate velocity at impact is $v = \sqrt{2gh}$, where $h = h_i - h_f$. Impact velocities for typical Charpy apparatus are in the range $3 \leq v \leq 6$ m/s [31]. The low end of this range corresponds with

FIG. 1 Charpy impact testing apparatus.

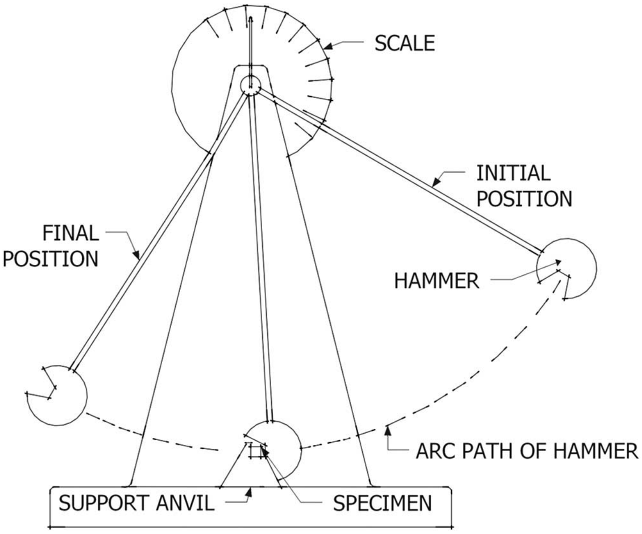
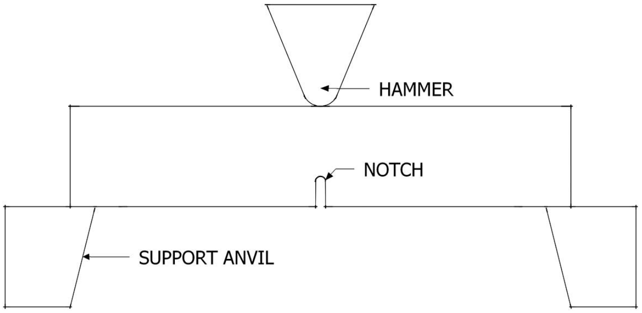


FIG. 2 Charpy specimen configuration (top view).



the theoretical impact velocity during the ACI 544.2R, *Measurement of Properties of Fiber Reinforced Concrete*, drop-weight impact test, wherein $h = 0.457$ m and v near 3 m/s. Resulting strain rates for both tests are of the order 10 s^{-1} [5].

Charpy Impact Testing of Cementitious Composites

Charpy impact tests have been performed on a wide variety of cementitious composites including mortar, concrete, ultra-high performance concrete (UHPC), and a variety of fiber-reinforced cements and mortars. At least 20 studies have reported results for Charpy impact tests of cementitious composites. The experimental details, including the material tested, the specimen geometry, the characteristic size of constituent materials, and normalization of results are somewhat inconsistent between authors. Specimen sizes ranged from 10 by 10 by 50–55 mm [35–38] to 100 by 100 by 500 mm [39]. Most included loading spans of 40 mm, but several reported much longer spans [39–41]. Most studies reported results for plain (unnotched) specimens, whereas a few reported results for notch depths near one fifth the specimen depth [42–44]. Aggregate and fiber sizes varied significantly, as did their sizes relative to the specimen dimension. Several different normalization procedures led to results being reported in units of energy, energy per unit length, energy per unit area, and others. A number of studies failed to report significant details including loading span [35–37,45–49], aggregate size [46,48], and fiber diameter [35–37,39]. These inconsistencies—which will be discussed in greater detail in the pages to come—limit the basis for comparison between studies and demonstrate a need for standardization of test methods and reporting procedures for Charpy impact testing of cementitious composites.

A majority of the studies that have evaluated the Charpy impact energy absorption of cementitious composites have evaluated fiber-reinforced concrete (FRC). This includes concrete reinforced with steel [39,41,50], ceramic [46], glass [39,49], polymer [42,48], and a variety of natural fibers [35–37,39] or fiber meshes [45,47,49]. It should be noted that Radomski [50] actually implemented a rotating impact machine but that study is included in the present discussion because the specimen size and type and the fundamental principles of the test are of interest to this discussion. These studies have mainly concluded that the impact strength of FRC depends on the type, dosage (volume), length, and orientation of the fibers. The fiber orientation is important in two senses: (1) whether the fibers are oriented uniformly in a single direction, randomly oriented, or somewhere between; and (2) the direction of the impact force relative to the predominate fiber orientation [50]. The impact energy absorption—and other properties—depend heavily on the properties of the fibers [46]. Several other studies have reported Charpy impact energy results for normal concrete [40], UHPC [38,43,44,51,52], and other advanced cementitious composites [53,54]. The results of these studies are too few and varied to report any significant findings.

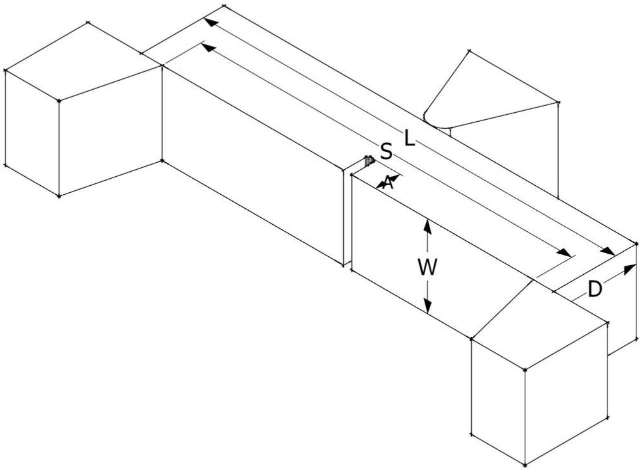
Specimen Size and Geometry

The effect of specimen size on the mechanical properties of concrete has been studied at length, with particular emphasis on the effect of specimen size on the fracture properties [55,56] and compressive strength [57,58]. ASTM C31, *Standard Practice for Making and Curing Concrete Test Specimens in the Field*, recommends that the diameter of cylindrical specimens used for the determination of compressive strength of concrete or the depth of beams tested in flexure be no less than three times the nominal maximum aggregate size [59]. Hibbert and Hannant [60], Radomski [50], and Kim et al. [15] have discussed specimen size requirements for impact testing of cementitious composites. Radomski suggested that the minimum dimension of impact test specimens be no less than five times the nominal maximum aggregate size, and no less than twice the fiber length unless sawn from larger blocks [50]. Kim et al. suggested that the minimum specimen dimension be no less than three times the characteristic dimension of the largest constituent.

The standard specimen size for the ACI 544 drop-weight impact test is 150 by 63.5 mm. Following the above recommendations, the maximum aggregate size for the ACI 544 drop-weight test is 12.7 mm and the maximum fiber length is either 31.8 mm or 21.2 mm. The former requirement may be relaxed if specimens are sawn from larger blocks [50], although Yalçinkaya et al. [38] specifically cite cracks resulting from saw-cutting as a source of variability in impact tests.

The geometry of a generalized Charpy specimen is shown in **Fig. 3**, where D is the depth, W is the width, L is the length, S is the clear span, and A is the notch depth (where applicable). The dimensions are expressed as W by D by L in the following discussion. Although Russell's original pendulum tests were performed using large specimens (as large as 25 by 50 by 600 mm) [22], the

FIG. 3 Specimen dimensions.



standard specimen dimensions for Charpy impact tests of metals are comparatively small (10 by 10 by 55 mm with 40 mm span) [26,32]. The relative homogeneity of metallic materials allows for the evaluation of impact strength with reasonable accuracy using specimens of small dimensions [50].

A variety of specimen sizes have been employed for Charpy impact testing of cementitious composites, as listed in **Table 1**. The most common specimen sizes are equivalent or very close to 10 by 10 by 50 mm [35–38], which is consistent with standardized methods for metals or 25.4 by 25.4 by 50.8 mm with 40 mm span [42–44,51,52]. The largest specimens were used by Al-Oraimi and Seibi [39], measured 100 by 100 by 500 mm, and required extensive modification to the Charpy testing apparatus. The ratio of maximum specimen size to minimum specimen size represented by the studies summarized in **Table 1** is approximately 10. Most of the studies listed in **Table 1** adhere to the aforementioned specimen size guidelines with respect to maximum aggregate size, with one noteworthy exception (the 9-mm maximum aggregate size employed by Gopalaratnam, Shah, and John [40] is more than one third the minimum specimen dimension of 25 mm). A few of the studies adhere to the specimen size guidelines with respect to fiber size (or nearly so) [38,42,45,48,51,52], but many include fiber lengths several times the minimum specimen dimension [35–37,46].

The small specimen sizes necessitated by the Charpy impact apparatus are certainly a limitation for Charpy testing of cementitious composites. Specimens of depth larger than about 25 mm require testing on heavily modified Charpy apparatus. Meanwhile, following the aforementioned specimen size guidelines [15,50,60], the maximum aggregate size and fiber length for such specimens are 5 mm and 12.5 mm, respectively. The former is more of a limitation than the latter, especially considering the saw-cutting provision listed by Radomski [50]. A maximum aggregate size of 5 mm precludes Charpy testing of most concretes but still allows for testing of cementitious composites with fine aggregates or no aggregates (e.g., hardened cement paste, mortar, or UHPC).

More concerning than the lack of dimensional consistency in Charpy impact specimen sizes between authors is the total lack of geometric similarity. Many authors report results from specimens of square cross section while others report results from specimens

TABLE 1 Summary of previous Charpy impact tests of cementitious composites.

		Specimen Geometry (mm)							
Ref(s).	Material	Width	Depth	Length	Span	Notch	Max Aggregate Size (mm)	Fiber Size (mm)	Reported Units
[50][a]	Steel FRC	15	15	105	54	None	2.0	40 × 0.40	J/m^2
[45]	Bamboo-mesh FRC	19	45	70	§[b]	None	1.41	5 × 0.88	J/m^2
[40][c]	Concrete	25	76	229	203	None	9.0	None	Rupture modulus
[41][c]	Steel FRC	25	76	229	203	None	5.0	25.4 × 0.41	Rupture modulus, Fracture energy
[39]	Steel, glass, palm FRC	100	100	500	450	None	10.0	30 × §	Ratio[d]
[46]	Ceramic FRC	10	20	80	§	None	§	3, 5, 10 × 0.003	Ratio[d]
[42]	PVA/PVB[e] FRC	25.4	25.4	50.8	40	5.1 (Saw-cut)	None	8 × 0.04	J/m
[35–37]	Sisal FRC	10	10	50	§	None	2.0	25, 45 × §	J
[47]	Cotton cloth-reinforced geopolymer	20	20	60	§	None	None	[f]	J/m^2
[53,54]	Nanoclay-cement composites	10	20	70	40	None	None	None	J/m^2
[38]	UHPC	10	10	55	40	None	1.0	6 × 0.16	J
[51,52]	UHPC	25.4	25.4	50.8	40	None	2.0	13 × 0.2	J
[48]	Aramid FRC	40	40	160	§	None	§	40 × 0.014	J/m^2
[49]	Glass mesh-reinforced cement	10	50	120	§	None	2.0	[g]	J/m^2
[43,44]	UHPC	25.4	25.4	50.8	40	5.0 (Formed)	0.595	None	J/m, J/m^2

Note: [a]Using a rotating impact machine fundamentally identical to Charpy test in theory of operation, [b]§ = unreported, [c]Using instrumented Charpy test, [d]Report ratio of performance of FRC/plain concrete without describing the basis for comparison, [e]Polyvinyl alcohol (PVA) and polyvinyl butyrol (PVB), [f]Using geopolymer-impregnated woven cotton cloth, [g]Using glass fiber mesh with spacing 5 × 5 mm.

whose depth is three to five times the width. Furthermore, specimen lengths range from as little as twice the width [42–44,51,61] to more than ten times the width [40,41,62]. The aspect ratio $\Phi = S / D$ is also inconsistent, ranging from 1.6 to more than 4. The behavior of specimens with short aspect ratio are more likely to be dominated by shear, whereas those with longer aspect ratio are more likely to be dominated by bending [63]. A number of studies neglect to report the specimen length, the span, or the characteristic dimension of the smallest constituent [35–37, 43–48,62]. This is bad practice and limits the interpretation of test results, precludes their comparison with those from other studies, and makes their reproduction impossible.

Normalization and Units

In addition to variations in specimen geometry, existing studies that employ Charpy methods for impact testing of cementitious composites also vary in how the data are reported. The results reported by the 20 aforementioned studies fall into a few distinct categories. Six studies representing three groups of authors report the impact energy directly without any normalization [35–38,51,52]. Two studies report the impact energy normalized by the specimen width (where width refers to the dimension across which the hammer strikes) in units of energy per length, i.e., force [42,43]. Eight studies report the impact energy normalized by the cross-sectional area at the impact location in units of energy per unit area, i.e., force per length [44,45,47,48,50,53,54]. A few others report relative results—for example the impact strength of fiber-reinforced specimens relative to that of unreinforced specimens—but with no discussion of whether the comparison is based on direct or normalized results [46,64].

Reporting impact energy without normalization allows direct comparison of the impact energies of specimens that are dimensionally identical but does not take into account the inevitable variations in specimen dimension. Normalization of impact energy by a single dimension also allows direct comparison takes into account the variation in a single specimen dimension but assumes that the remaining dimension is deterministic. Normalization by both cross-sectional dimensions is far superior because it takes into account the inevitable variation in both dimensions and—where appropriate—in the dimensions of the fabricated crack. In any case, comparisons are limited to specimens that are geometrically similar.

The few studies that employ the instrumented Charpy method generally report the dynamic modulus of rupture in units of stress or the dynamic fracture energy in units of energy per unit area [40,41]. The latter is fundamentally similar to the impact energy normalized by the area of the fracture surface (i.e., the cross-sectional area at the impact location), but clear distinction between the two is appropriate because of the uncertainties associated with the traditional (noninstrumented) Charpy test. The dynamic fracture energy as determined by the instrumented Charpy test can be directly compared to the static fracture energy (considering relevant size effects), whereas the impact energy per unit cross-sectional area cannot.

Notched Bar Impact Testing

In the late 19th century, when impact testing methods were limited to rudimentary drop-weight tests, LeChatelier [65] found that crack initiation was difficult to achieve in ductile metals. Provision of a notch in the tension face promoted crack initiation and fracture in ductile materials that would otherwise fail by yielding [27,65]. When introducing the pendulum impact test, Russell [22] presented results for both notched and plain specimens. Some readers claimed that results for notched specimens were of "doubtful utility" because of the stress concentration at the notch tip [66], sparking a contentious response from Russell [67]. Acknowledging the "remarkable influence" of notch geometry and formation method, Charpy [23] proposed an alternative notching procedure consisting of a saw cut terminated by a drilled hole—a keyhole notch—which provided a more uniform and blunt notch tip. Recent revision of the ASTM E23, *Standard Test Method for Notched Bar Impact Testing of Metallic Materials* [31], method for Charpy impact testing of metals allow for one of three notch geometries: the chevron notch, the keyhole notch, and the sawn notch, as shown in **Figs. 4–6**. Relevant standards specify only that notch faces must be smoothly machined and free of undulations or machine marks that may affect test results [31,32].

FIG. 4 ASTM E23 chevron notch [31] (dimensions in mm; span is 40 mm).

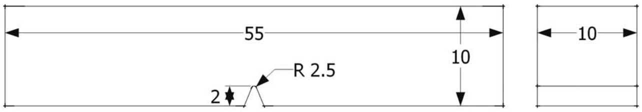


FIG. 5 ASTM E23 keyhole notch [31] (dimensions in mm; span is 40 mm).

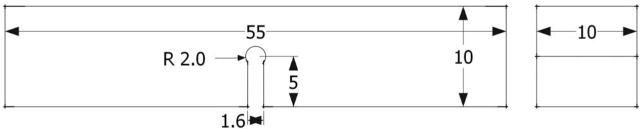
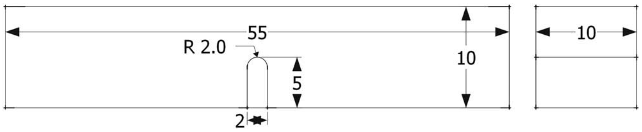


FIG. 6 ASTM E23 sawn notch [31] (dimensions in mm; span is 40 mm).



The overwhelming majority of studies summarized in **Table 1** report Charpy test results for plain (unnotched) specimens. Bedke [43] and Thomas, Bedke, and Sorensen [44] present results from Charpy tests of chevron-notched UHPC, where notches were formed in fresh concrete using a poly(methyl methacrylate) bar. The results of these test were widely scattered [43,44], which was attributed to variability in the formed chevron notches [44]. Lavin et al. [42] presented results from Charpy tests of PVA- and PVB-reinforced cements with saw-cut notches and did not report prohibitively high variability. If notches are to be provided, saw-cutting is arguably preferable. Saw-cut notches can be fabricated with ease and repeatability using ordinary wet diamond rotary blades. It is also worthy of mention that the choice between forming notches in fresh specimens versus cutting notches in hardened specimens will significantly affect fiber orientation. In the former case, the fibers will be pushed from their original orientation and become preferentially aligned with the forming tool. In the latter case, the fiber orientation will be unaffected by notch formation.

None of the authors—neither those who tested notched specimens nor those who tested plain specimens—offer any comments with respect to the motivation for doing so. Admittedly, concrete and other cementitious composites are unlikely to exhibit the ductility that proved problematic for LeChatelier [65]. Even so, fracture tests of cementitious composites are performed almost exclusively using notched three-point bend specimens. In these tests, the notch serves as a Griffith crack of known size from which the fracture plane can propagate. Furthermore, there is precedent for providing notches in impact specimens of cementitious composites. Badr and Ashour [25] showed that the reliability of the ACI 544 drop-weight impact test was greatly improved when two diametrically opposed chevron notches were cut into the radial faces of the test specimen. In that same study, tests in which the fracture line did not propagate from the fabricated notch tips were discarded. However, no studies to date have investigated the question of notched versus plain specimens for Charpy impact testing of cementitious composites. Studies that address this topic would be of great utility to the development of a standardized test method for the same.

Criticisms of the Charpy Method

Criticisms of the Charpy method mainly relate to the qualitative nature of the measurement [5]. Abe, Chandan, and Bradt [68] suggested that the energy reported by the Charpy apparatus overestimated the actual energy absorption during fracture of the Charpy specimen. Others have corroborated this supposition, showing that significant energy losses exist because of inertial effects [62,69,70]. Instrumented Charpy tests [40], which employ a series of high-frequency strain and linear position sensors and can measure the load and deflection during the impact event, have been introduced in an attempt to evaluate the true impact energy absorption during the Charpy test. These tests indicate that the Charpy specimen does not experience a single impact event; instead, the load is applied as a high frequency decaying sawtooth waveform [40]. Results from such instrumented Charpy tests have been presented for both plain concrete and FRC [40,41], but the complexity of the required apparatus seems to have limited its application. Using the resulting strain energy absorption data, authors have reported results for dynamic fracture toughness. It should be noted, however, that the calculations presented by Dempsey, Wei, and DeFranco [71] suggest that the specimen size used for Charpy tests renders these results meaningless from a fracture mechanics standpoint. Dempsey, Wei, and DeFranco [71] showed that specimens become notch insensitive when the crack ligament is less than about four times Hillerborg's characteristic length [72]. This is of particular importance for fiber-reinforced cementitious composites, where improved ductility increases the characteristic length and reduces notch sensitivity.

The ACI 544 drop-weight impact test results are reported as the number of successive blows resulting in failure. Meanwhile, the Charpy impact test results are reported in units of energy. Even if the standard (noninstrumented) Charpy apparatus is employed, wherein the measured energy is known to overestimate the actual energy absorbed by the specimen, the results are arguably more quantitative than those from the drop-weight test.

The remaining criticism would relate to the application of the Charpy test to cementitious composites given the previously discussed specimen size limitations. In this context, the Charpy test is admittedly ill-equipped for impact testing of concrete containing coarse aggregates. Other cementitious composites should however present no problem as long as the aggregate size is limited to one fifth the minimum specimen dimension.

Summary

Though mainly applied to impact testing of metallic and polymeric materials, the Charpy impact test has seen some use for characterization of cementitious composites under impact loading. This includes applications of the Charpy impact test to mortar, concrete, UHPC, and a variety of fiber reinforced cements. These studies have reported a wide range of impact energy absorptions. The lack of a standardized method for Charpy testing of cementitious composites has led to a great deal of variation in execution between authors. In particular, the specimen geometries and spans employed have been quite inconsistent. Little attention has been paid to the size of constituent materials relative to the specimen dimensions. Some authors have chosen to test notched specimens, whereas other have tested plain specimens. There has not even been a consistent approach to the normalization of impact energy absorption data. In general, it is difficult if not impossible to compare results between studies performed by different authors. This is a clear demonstration of the need for a standardized test method for Charpy impact testing of cementitious composites. Standardized test methods are already in existence for drop-weight impact testing of cementitious composites, but that method is arguably more qualitative in nature than the Charpy test.

This discussion highlights inconsistencies in the literature with respect to specimen size, aspect ratio, notch depth, and other parameters for Charpy impact testing of cementitious composites. Based on the literature and mechanical principles summarized here, some recommended best practices are listed below.

- The minimum specimen dimension should be no smaller than five times the characteristic size of the largest constituent [15,50,60]. This requirement may be relaxed in the case of fiber-reinforced cementitious composites if specimens are sawn from larger blocks [50]. Many authors have reported successful testing using specimens measuring 10 by 10 mm [35–38] or 25 by 25 mm in cross section [42–44,51,52].
- There is little mention of the benefits of notching in the literature, and the degree to which they are important is unknown. If notches are provided, they should be saw-cut in hardened concrete. Forming notches in fresh concrete [43,44], milling chevron notches, or providing keyhole notches by rotary impact drilling are not recommended. A few authors have reported on testing using notch depths equal to one fifth the specimen depth [42–44].
- Attention should be paid to aspect ratio, which affects whether the tensile or shear behavior controls failure [63]. A number of authors have reported success with both shallow aspect ratios similar to those prescribed for Charpy testing of metals and plastics (10 mm depth with 40 mm span) [35–38], which favor tensile failure, and deep aspect ratios (25 mm depth with 40 mm span), which favor shear failure [42–44,51,52].
- It is vital for authors to report full details regarding specimen size (cross-section, length, and span) and notching, as well as the characteristic sizes of constituent materials.

Several important points are not sufficiently addressed by existing literature, which are outlined below.

- The effects of specimen size and aspect ratio are not well defined. Finite element modeling and experimental evaluations would show the ideal aspect ratios for evaluating impact performance of concrete structures.
- The most logical means of normalizing the impact energy absorption is unknown. Potential normalization schemes include normalizing by the specimen depth or cross-section, or by some factor of the span and cross-section (as in the rupture modulus or flexural stress).
- The notch sensitivity of cementitious composite Charpy specimens is not well understood. Research in this area would help determine if notching is appropriate for this type of testing and, if so, to optimize the notch depth and formation procedure.
- There is a need to compare the results from Charpy test to those from drop-weight impact tests as well as large-scale impact tests.

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