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Report on the Measurement of Fresh State Properties and Fiber Dispersion of Fiber- Reinforced Concrete

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Report on the Measurement of Fresh State Properties and Fiber Dispersion of Fiber-Reinforced Concrete

Reported by ACI Committee 544

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Henry J. Molloy

Antoine E. Naaman
Venkataswamy Ramakrishnan

*Members of subcommittee who contributed to the document.

†Chair of the Subcommittee C who developed the document.

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This report outlines existing procedures for testing and measuring fresh state performance and fiber dispersion in fiber-reinforced concrete (FRC). As for the former, test methods applicable to both ordinary vibrated FRC and fiber-reinforced self-consolidating concrete (FR-SCC) are reviewed. Methods for nondestructive monitoring of fiber dispersion and orientation in FRC materials and structures are also presented and their pros and cons addressed.

Keywords: fiber dispersion; fiber-reinforced concrete; fiber-reinforced self-consolidating concrete; fresh state performance; nondestructive testing.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The use of fiber-reinforced concrete (FRC) has evolved from experimental small-scale applications to routine factory and field applications involving the use of tens of millions of cubic yards (meters) each year globally. This has created a need to review existing test methods and, where necessary, develop new methods for determining the fresh and hardened properties of FRC that may be of interest for different engineering applications and may be required at different stages of the design, construction, and maintenance process. These methods are presented in an effort to standardize test procedures and equipment, and also to ensure that test results from different sources can be compared effectively. Whereas it is recognized that the use of procedures and equipment other than those discussed in this report may be employed because of past practices or availability of equipment, the use of standard tests facilitates the comparison of information, promotes the development or broadening of the data base needed to consistently quantify properties of the various types of FRC, and is preferable to nonstandard variants. Such data are also instrumental in developing consistent and internationally recognized design procedures that are based on standard measurements of relevant properties of the material, as well as in formulating reliable performance criteria to classify and accept the material.

Although most of the test methods described in this report were developed initially for steel FRC (SFRC), they are also applicable to concretes reinforced with glass, polymeric, and natural fibers, except when noted.

As the applications of FRC are being expanded and new fibers are introduced to the market, some existing test methods may be found insufficient or unable to provide meaningful data. Therefore, changes can be applied and, in these instances, care taken in consideration of the issues of repeatability and reproducibility of test results. Repeatability is defined as the variability among replicate test results obtained on the same material within a single laboratory or job site by one operator. Reproducibility refers to variability among test results obtained on the same material in different laboratories, job sites, or both. Regarding reproducibility, users are advised to carefully check the applicability of the test methods, both in lab conditions and in the field, as differences may exist between them.

1.2—Scope

This report applies to the measurement of fresh state and fiber-dispersion properties of both conventionally mixed and placed (vibrated) FRC and fiber-reinforced self-consolidating concrete (FR-SCC) using steel, glass, polymeric carbon, minerals (such as basalt), and natural fibers.

The test methods reported herein are also applicable to ultra-high-performance concrete (UHPC). It is worth remarking that, generally, UHPC does not contain coarse aggregates and is employed in combination with reduced or no amounts of conventional reinforcement. In view of this, care should be taken in assessing the significance of the results, as far as the consistency is concerned, of the volume of material employed in the tests with reference to the heterogeneity scale of the mixture (maximum aggregate size, maximum fiber length). Moreover, passing ability tests, such as the ones reviewed in 3.2.2, may also provide information of limited significance.

This report does not relate to thin glass FRC or mortar products produced by the spray-up process. The [Prestressed Concrete Institute \(1981\)](#), [International Glassfibre Reinforced Concrete Association \(2016a,b\)](#), and [ASTM C1116/C1116M](#) contain recommendations for test methods for these spray-up materials.

Measurement of the properties of fiber-reinforced shotcrete (FRS) that contain the aforementioned fiber types can be performed using the test methods described herein. Special procedures may be required to cast specimens or obtain them from existing structures, as well as to measure properties specific to shotcreting technology. Relevant provisions can be found in [ACI 506.2](#).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

c	=	clear gap spacing in L-box test
d_f	=	fiber diameter, in. (mm)
d_{max}	=	maximum diameter of the flow spread in J-ring test, in. (mm)
d_{perp}	=	diameter measured perpendicular to the maximum diameter d_{max} in J-ring test, in. (mm)
l_f	=	fiber length, in. (mm)
R	=	electrical resistivity of fiber-reinforced concrete or fiber-reinforced cementitious composite, ohm
R_m	=	electrical resistivity of the parent plain concrete (matrix), ohm
T_{20} or T_{500}	=	time for the flow spread to reach a diameter of 20 in. (500 mm) in slump flow test, s (in European literature, it has been referenced as T_{50} , where 50 represents the threshold diameter in cm)
T_{final}	=	time for the flow spread to reach the final slump-flow diameter in slump flow test, s
T_V	=	V-funnel flow time, that is, time for the fluid concrete filling the funnel to completely come out once the nozzle of the funnel is opened, s
V_f	=	fiber volume fraction (generally expressed as percentage)
γ	=	filling capacity in filling box test

- $\dot{\gamma}$ = shear strain rate, applied to a fluid (in a rheometer test), s^{-1}
- μ = plastic viscosity (in Bingham fluid model), that is, resistance of the fluid (concrete) to flow once the value of the yield stress has been overcome, psi-s (Pa-s)
- σ = electrical conductivity of fiber-reinforced concrete or fiber-reinforced cementitious composite – inverse of R (Siemens)
- $[\sigma_{fiber}]$ = intrinsic conductivity of fiber (Siemens)
- σ_m = electrical resistivity of the parent plain concrete (matrix) – inverse of R_m
- τ = shear stress applied to a fluid (in a rheometer test), psi (Pa)
- τ_0 = yield stress, that is, value of the shear stress that has to be overcome for the fluid (concrete) to start flowing (in Bingham fluid model), psi (Pa)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <https://www.concrete.org/store/productdetail.aspx?ItemID=CT13>. Definitions provided herein complement that source.

dynamic segregation—in a fluid concrete flow, separation of concrete constituents along the flow direction as a function of their specific gravity (heavier constituents tend to lag behind because of insufficient viscosity of the suspending phase to drag them ahead).

fiber aspect ratio—ratio of the length to the diameter of one single fiber or fiber filament.

fiber volume fraction—total fiber volume in a unit volume of concrete (generally expressed as a percentage).

fiber factor—product between the fiber volume fraction and the fiber aspect ratio.

specific surface area—total lateral surface area of a unit mass quantity of a given powder type/granular material or assortment of materials; it depends on the grain size distribution of the particles and on the specific gravity of the material.

static segregation—separation, in a fluid concrete mixture when at rest, of its constituents, as a function of their relative specific gravity (heavier constituents tend to settle because of insufficient yield stress of the suspending phase to hold them in suspension).

CHAPTER 3—FRESH STATE PROPERTIES

3.1—Sampling, unit weight, yield, and air content

To perform the tests described in this chapter to measure the fresh state properties of fiber-reinforced concrete (FRC), the sampling procedures outlined in **ASTM C172/C172M** and **EN 12350-1** for conventional concrete should be applied.

Similarly, standard test equipment and procedures used for conventional concrete can be employed for determining the air content, yield, and unit weight of FRC (**ASTM C138/C138M**; **ASTM C173/C173M**; **ASTM C231/C231M**; **EN 12350-6**; **EN 12350-7**). Because of the alteration in fiber dispersion and orientation that may result from specimen preparation, the specimen molds should be filled in one lift. Consolidation may result in alteration in fiber dispersion

and orientation. Because of this, samples should be consolidated, when applicable, using external or internal vibration as permitted by **ASTM C31/C31M** and **ASTM C192/C192M** only when the fiber orientation is not an issue, regarding the performance to be measured. Rodding should not be applied.

3.2—Workability and fresh state performance

3.2.1 Workability tests for conventional vibrated FRC—Workability is defined as that property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogeneous condition. The presence of fibers can result in specific issues that require incorporation into the broad definition of workability, as stated previously and in related measuring techniques. This will be addressed more in this report. Workability is generally assessed using the following simple field tests.

3.2.1.1 Slump test—The slump test (**ASTM C143/C143M**; **EN 12350-2**) is a common, convenient, and inexpensive test, but it may not be a good indicator of workability for FRC. The addition of fibers hinders the flow behavior of fresh concrete, especially if no adjustment is made to the mixture composition (**Bayasi and Soroushian 1992**). An example is the rearrangement of coarse aggregate grading in consideration of the effects of fibers on the void ratio of the solid particle skeleton (**Ferrara et al. 2007**). Therefore, the addition of fibers can lead to a decrease in the measured slump with increasing the fiber factor, which is the product of the fiber volume fraction and the fiber aspect ratio. The rate of change in the measured slump with the fiber factor is directly related to the fiber type (**Mangat and Swamy 1974**; **Swamy and Mangat 1974**; **Hughes and Fattuhi 1976**; **Bayasi and Soroushian 1992**). In this respect, because slump is a simple visual measurement, the exact meaning of the measured slump may become questionable if merely compared to that of the mixture with no fibers. The real workability of a FRC can be better evaluated by measuring, for example, the mixing energy required to work the given FRC to the target casting condition (**Chopin et al. 2004**; **Cazacliu and Roquet 2009**). However, once it has been established by preliminary testing that a specific FRC mixture has satisfactory handling and placing characteristics at a given slump, with respect to the intended application, the slump test may be used as a quality control test to monitor the FRC consistency from batch to batch.

3.2.1.2 Vebe test—The Vebe consistometer test, described in **EN 12350-3**, measures the behavior of concrete subjected to external vibration and is acceptable for determining the workability of concrete placed using vibration, including FRC. It effectively evaluates the ability of FRC to flow under vibration, and helps to assess the ease with which entrapped air can be expelled.

The apparatus is placed on top of a vibrating table. The fresh concrete is compacted into a conical slump mold. The mold is removed and a clear plastic disc is placed on the top of the concrete. The vibrating table is started and the time taken for the transparent disc to be fully in contact with the concrete (the Vebe time), is measured. Similar to the slump test, the

addition of fibers to a plain concrete matrix may lead to an increase of the Vebe time (Bayasi and Soroushian 1992).

Information from either the slump test, Vebe test, or both, can be useful for comparing mixtures and evaluating the effects of mixture-design changes, processing strategies, or both. This information can be useful to achieve a level of fresh state performance that is satisfactory for the application.

3.2.2 Fresh state performance tests for fiber-reinforced self-consolidating concrete—Since its appearance in Japan in the mid-1980s (Okamura 1997; Okamura et al. 2000), self-consolidating concrete (SCC) has gained popularity and is now widely used in the construction industry. Thanks to the synergy of SCC and FRC technologies, a new category of cementitious composites has been developed, referred to as fiber-reinforced self-consolidating concrete (FR-SCC). FR-SCCs exhibit excellent performance in both the fresh and hardened state. Resulting from their adapted rheology, FR-SCCs can also exhibit improved fiber dispersion compared with conventional vibrated FRCs (Ferrara 2014).

The concept of workability, as defined previously with reference to conventional vibrated concretes, is insufficient to describe the many aspects of the fresh state performance of SCC. Other important characteristics include flowability; filling and passing ability; and issues related to specific applications, including resistance to static and dynamic segregation of fibers as further clarified in 3.2.3. The ability to disperse the fibers along the casting flow represents the key distinctive feature of FR-SCC. To assess the aforementioned characteristics, both qualitatively and quantitatively, specialized testing methods and equipment have been designed and calibrated, as reviewed in ACI 237R and ACI 238.1R. These test methods have been established to evaluate the fresh state performance of plain SCC, which can be valid also for FR-SCC mixtures. The most common test methods used in practice will be herein reviewed, and a summary table will be provided at the end of the document, with an attempt to address the most peculiar issues that should be accounted for when performing them on an FR-SCC.

FR-SCC featuring acceptable fresh state performance cannot be obtained by merely incorporating the fiber reinforcement into an SCC matrix. The paste phase composition, the aggregate solid skeleton, or both, should be adapted through void ratio (ASTM C29/C29M) and particle-specific surface area concepts (Ferrara et al. 2007). The following issues should be considered when either performing tests or evaluating existing test data regarding the fresh state performance of FR-SCC:

a) The influence of the fiber addition on the fresh state performance of the parent matrix

b) The significance of limit values for indicators of fresh state performance measured through different tests, also in the framework of a prescription to performance approach

3.2.2.1 Slump flow test—The simplest and most widely used test method for FR-SCC is the slump flow test, which is the same used for plain SCC (ASTM C1611/C1611M; EN 12350-8). The slump flow test is used to assess the horizontal free flow of SCC in the absence of obstructions and is

correlated to the initial resistance to flow of the fluid mixture (yield stress).

To perform the test, the same equipment used for the lump test is required. Once filled, the cone is lifted, and, after the free flow of the concrete has finished, the total horizontal spread, or slump-flow diameter, is measured. Acceptable ranges for the slump-flow diameter as well as recommended values for specific applications can be found in EN 206-9, ACI 237R, and EFNARC 2002.

Information on the flow rate of SCC—a measure of its viscosity—can be inferred from slump flow tests by measuring the time required for the concrete to spread to a diameter of 20 in. (500 mm), generally denoted as T_{50} or T_{500} . Limit values of T_{50} for defining viscosity classes of SCC and related classification can be found in ACI 237R and EN 206-9. Concrete mixtures featuring higher T_{50} values will also exhibit thixotropic effects that may be good for limiting formwork pressure (Lomboy et al. 2014; Tichko et al. 2015) and improving segregation resistance, but may also lead to surface-finish issues (such as bugholes) (da Silva and Štembek 2013) and sensitivity to stoppages or delays between successive lifts. Concretes with lower T_{50} values will also exhibit good filling ability, even with congested reinforcement, and improved self-leveling ability and best surface finish, but they will be more likely to suffer from bleeding and segregation.

Tregger et al. (2012) states that the time required for the spread flow to stop (T_{Final}) is likely to correlate better with the viscosity of the fluid concrete than T_{50} . As shown in Fig. 3.2.2.1, investigation focuses on two families of SCC mixtures, characterized by two values of slump-flow diameters, and, for each value of the slump-flow diameter, by different contents of viscosity-modifying admixtures (VMAs), resulting in different values of the viscosity. A visual stability index has been proposed as a standard means of determining segregation stability of a mixture (Khayat et al. 2000; Ferrara et al. 2007). A numerical score on a scale of 0 (no evidence of segregation or bleeding) to 3 (clear evidence of a segregating mortar halo greater than 3/8 in. [10 mm], large aggregate pile and fiber clumps in the center of the concrete mass, or both) is assigned based on a visual evaluation of the segregation and bleeding in the sample. The subjectivity of this score limits its usefulness.

Studies have been performed to identify parameters, measurable from the slump flow test, that correlate with the resistance of the fluid mixture to dynamic segregation of solid particles, including coarse aggregates and fibers. The time required for the spread flow to stop (T_{Final}) has been correlated to the resistance of the fluid mixture to dynamic segregation of coarse aggregates and fibers (Tregger et al. 2012; Ferrara et al. 2012a). In this respect, threshold values of T_{Final} to be used for quality control of SCC batches can be calibrated and selected depending on the level of resistance to dynamic segregation that is acceptable for the intended application. The selected casting procedure (pouring system and height, and maximum flow distance) can influence the selected threshold values.

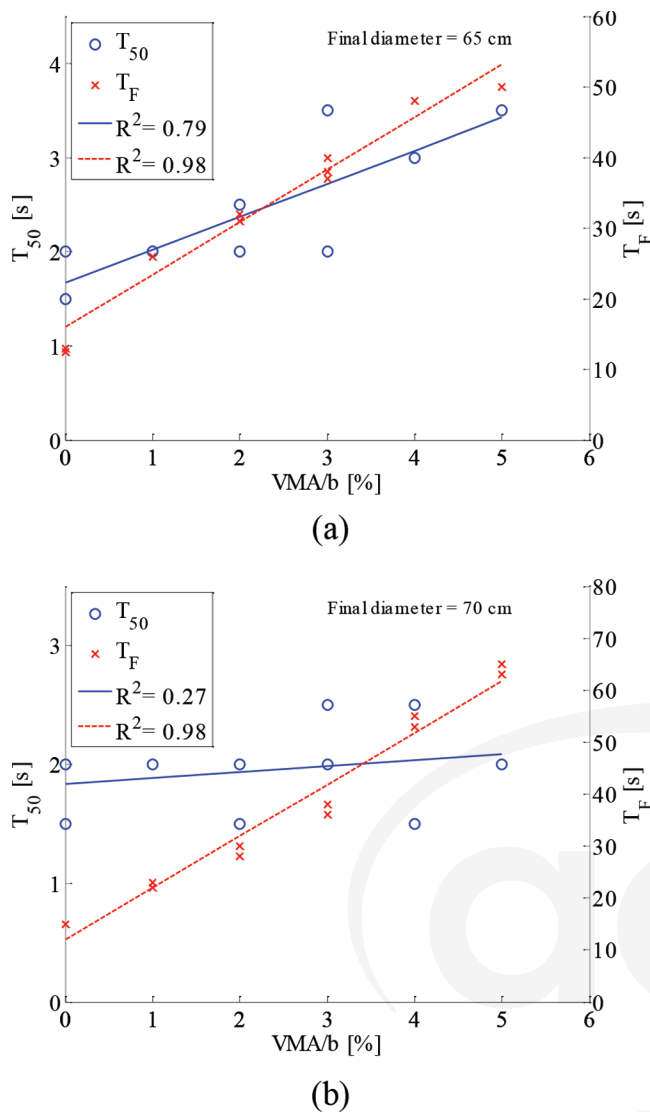


Fig. 3.2.2.1—(a) Time to 20 in. (500 mm) spread (T_{50}); and (b) time to final spread (T_F) for SCCs featuring the same slump-flow diameter but different content of viscosity-modifying admixtures (VMAs), resulting in different relative viscosity (Tregger et al. 2012). (Note: 1 in. = 25.4 mm.)

Ferrara et al. (2012a) have shown that a correlation between slump-flow parameters and fiber dispersion can be established, as discussed in 3.2.3 and shown in Fig. 3.2.3b and 3.2.3c.

3.2.2.2 V-funnel test and V-funnel test at $T = 5$ minutes—The V-funnel test is used to measure the filling ability of SCC (EN 12350-9) and can also be used to judge segregation resistance (EFNARC 2002; Bartos et al. 2002). The typical test apparatus is shown in Fig. 3.2.2.2.

The test consists of filling the entire funnel with concrete without tamping or vibration, and measuring the time it takes for all the concrete to exit the funnel once a door at the bottom of the funnel is opened and concrete is allowed to flow out into a bucket. EN 206-9 prescribes limit values of V-funnel time (T_V) for the definition of funnel-viscosity classes of SCC and related classification.

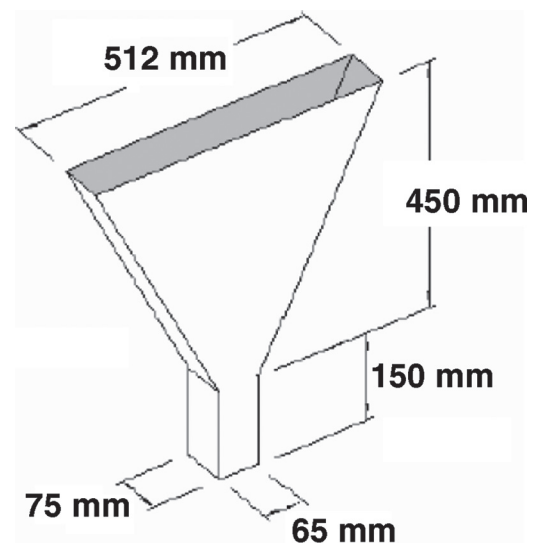


Fig. 3.2.2.2—V-funnel test apparatus (from EN 12350-9). (Note: 1 in. = 25.4 mm.)

To measure segregation resistance (Bartos et al. 2002), the V-funnel is filled with the concrete, which is allowed to sit for 5 minutes. The door is opened and the flow time is recorded. A larger increase in flow time after the concrete has remained at rest for 5 minutes indicates a concrete's higher susceptibility to segregation.

For FR-SCC, the same standard equipment as for SCC has been used (Ferrara 2014), and the same limit values for V-funnel time have been found adequate for a wide range of FR-SCC compositions, featuring up to 1 percent by volume of either steel or synthetic macrofibers, up to 1.6 in. (40 mm) long. Grünwald (2004) used a funnel with a nozzle that was twice as long and with four times as large of an opening to have consistent results for higher dosages of fibers (up to 2 percent by volume) with lengths up to 2.4 in. (60 mm).

Similar to slump-flow measurements, T_V has been correlated with susceptibility of FR-SCC mixtures to statically and dynamically segregate.

3.2.2.3 L-box test—The L-box test measures the filling and passing ability of SCC (EN 12350-10; EFNARC 2002; Bartos et al. 2002). The apparatus consists of an L-shaped box, as shown in Fig. 3.2.2.3. Various dimensions for the L-box have been used (Ferrara 2014); Fig. 3.2.2.3 shows the one standardized in EN 12350-10.

In the most common arrangement, three 1/2 in. (12 mm) bars are spaced with a clear spacing of 1-5/8 in. (41 mm) (Fig. 3.2.2.3b), although an alternative arrangement of two 1/2 in. (12 mm) bars with a clear spacing of 2-1/3 in. (59 mm) (Fig. 3.2.2.3c) is also permitted by EN 12350-10. The choice of bar arrangement depends on the congestion of reinforcement expected for the project and the maximum aggregate size.

The test is performed by filling the hopper of the L-box, without any mechanical compaction and with the gate between the vertical and horizontal sections closed. Concrete is leveled at the top of the vertical section and allowed to rest for 60 seconds. The sliding gate is then fully opened to allow the concrete to flow into the horizontal section, passing between the bars. The passing ability of the concrete

Table 3.2.2.3—Clear gap spacing to fiber length ratio (c/l_f) as a function of fiber aspect ratio (l_f/d_f) and maximum fiber dosage (Groth and Nemegeer 1999)

c/l_f	l_f/d_f	Maximum fiber dosage, lb/yd ³	Maximum fiber dosage, kg/m ³
≥ 3	80	50	30
	65	100	60
≥ 2	65	50	30
	45	100	60
≥ 1.5	45	50	30

Note: Dosages are referring to steel fibers; conversion through equivalent fiber volume fraction and fiber unit weight should be applied in the case of other fibers such as glass and synthetic.

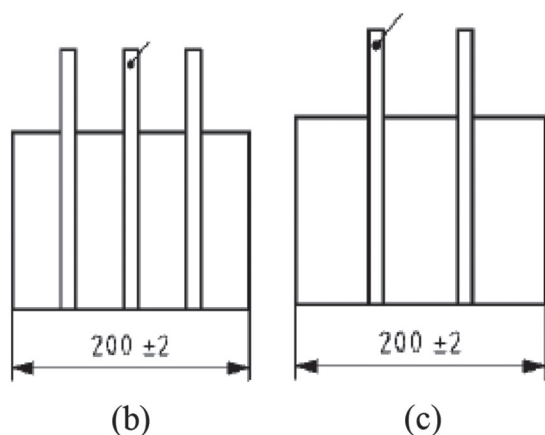
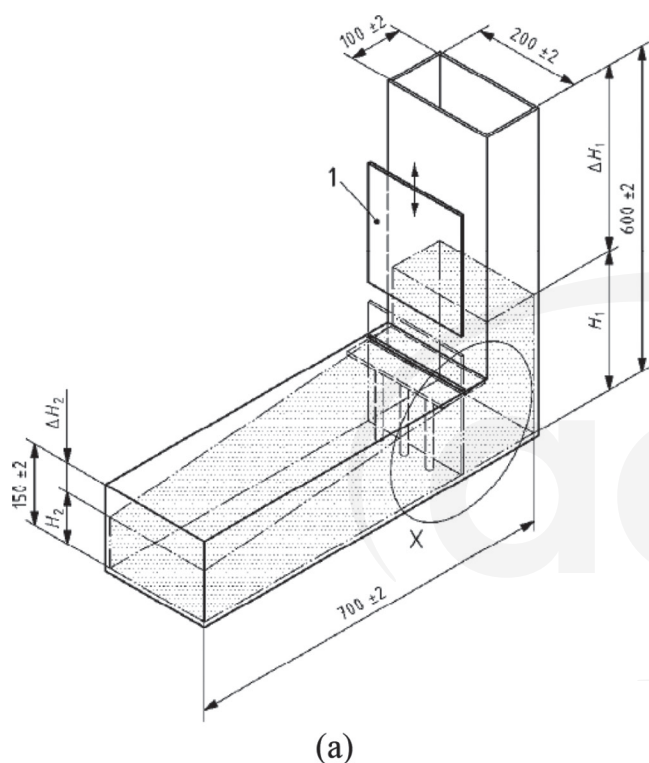


Fig. 3.2.2.3—(a) L-box test apparatus; (b) details of the alternative configuration of bar arrangement with clear bar space 1-5/8 in. $\pm$ 0.04 in. (41 $\pm$ 1 mm); and (c) with clear bar space 2-1/3 in. $\pm$ 0.04 in. (59 $\pm$ 1 mm) (EN 12350-12). (Note: 1 in. = 25.4 mm.)



Fig. 3.2.2.4—Modified J-ring test steps employed by Kassimi (2013).

is assessed from the ratio between the heights of the concrete measured at the far end of the horizontal portion, H_2 , and in the vertical section. As per EN 206-9, a concrete sample that reaches the far end of the horizontal part of the box with a height ratio not lower than 0.8 is deemed to have a good passing ability.

When used to measure the passing ability of FR-SCC, the standard L-box test may be too demanding because the narrow gap between the bars, which is comparable to the fiber length, is representative of high reinforcement congestion that can often be avoided with the use of fibers. To overcome the aforementioned drawback, the use of a variety of arrangements has been proposed (for example, one bar or no bars) (Kassimi 2013). Groth and Nemegeer (1999), with reference to steel fibers, proposed a minimum ratio of bar spacing c to fiber length l_f to avoid blocking, which is also a function of fiber content and aspect ratio l_f/d_f (Table 3.2.2.3). Grünewald (2004) highlighted the dependence of the blocking bar spacing on the mixture composition and on other fresh state properties of the FR-SCC. The effect of the fibers on the passing ability increased at decreasing slump-flow diameter (Grünewald and Walraven 2010).

Macrosynthetic fibers, which are not rigid like steel ones, may have less of an issue with this type of passing ability test.

3.2.2.4 J-ring test—The passing ability of SCC can also be determined using the J-ring test, as described in ASTM C1621/C1621M and EN 12350-12. The test consists of an inverted-cone slump flow test performed with the slump cone in the middle of the J-ring apparatus, as shown in Fig. 3.2.2.4. Alternative bar configurations with different clear spacing have been proposed by Kassimi (2013).

The J-ring flow is calculated as the average between the largest diameter (d_{max}) of the spread area and the diameter at 90 degrees to the largest diameter (d_{perp}). According to ASTM C1621/C1621M, the difference between the slump-flow and the J-ring flow diameter is an indication of the passing ability of the concrete, which is deemed satisfactory if the difference is less than 1 in. (25 mm). A difference greater than 1 in. (25 mm) would indicate poor passing ability.