Journal of Modern Engineering and Academic Research (JMEAR) ISSN (online): 4321-743X
Volume 5, Issue 1, 2026

Steel Fibre Geometry and Dosage in Concrete

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Abstract

Steel fibres can improve the mechanical response of concrete, but their effectiveness depends on geometry, dosage, matrix properties and the production process. This critical narrative review examines these dependencies with emphasis on workability, compressive strength and tensile performance. Selected primary studies on fibre type, aspect ratio, fresh properties, mechanical strength, pull-out and orientation are compared. The evidence supports a distinction between nominal fibre content and effective reinforcement at a crack plane. Increasing dosage may increase available crack bridging while also making the fresh mixture harder to place. Aspect ratio provides useful geometric information, but it does not represent fibre shape, bond behaviour or orientation by itself. Peak compressive strength, splitting tensile strength, residual flexural resistance and toughness are separate outcomes and should not be treated as interchangeable measures of improvement. A comparison framework is developed around explicit dosage denominators, measured fibre dimensions, matched matrix controls, documented casting and test-specific acceptance criteria. The synthesis identifies why an apparently optimal fibre percentage or aspect ratio is usually specific to the tested material system. Particular attention is given to transferring evidence from hooked or crimped fibres to zigzag fibres, for which equivalent nominal proportions do not establish equivalent performance. Future experiments should jointly evaluate fresh consistency, independent-batch variability and post-cracking response. The review provides a practical basis for designing and interpreting concrete experiments using deformed steel fibres without inferring structural suitability from peak-strength results alone.

Keywords: steel fibre reinforced concrete; zigzag steel fibre; fibre geometry; aspect ratio; dosage; workability; compressive strength; splitting tensile strength.

1 Introduction

Steel fibre reinforced concrete combines a cementitious matrix with discontinuous steel reinforcement. The response of that composite cannot be defined by fibre percentage alone. Soroushian and Bayasi [1] investigated the role of fibre type, while Bayasi and Soroushian [2] examined fresh mixtures containing different fibre shapes, lengths and contents. Their work establishes geometry and production as experimental variables that belong alongside dosage in any comparison of steel fibre concrete.

A second distinction concerns the measured property. Song and Hwang [3] studied high-strength steel fibre concrete, while Thomas and Ramaswamy [4] evaluated multiple mechanical properties. These studies motivate property-specific interpretation. A percentage increase in splitting tensile strength should not be presented as the same increase in compressive strength, and neither is a direct measurement of residual capacity after a crack opens. A review should preserve the identity of each test before comparing the magnitude of an improvement.

The subject is especially relevant when a laboratory study uses short zigzag fibres and reports only cube and cylinder peak strengths. A result obtained at one geometry can support a dosage comparison within that experiment, but cannot establish that the geometry is better than an untested alternative. Conversely, a general review of hooked or crimped fibres can suggest mechanisms and experimental controls without supplying missing zigzag test results. The present paper keeps those evidence boundaries explicit.

The review addresses four questions. How do geometry and dosage interact with fresh consistency and mechanical response? What does aspect ratio describe, and what does it omit? Which comparisons are needed to interpret peak strength and post-cracking performance? What reporting and experimental procedures would make a zigzag-fibre programme reproducible? The contribution is a structured interpretation of these questions rather than a pooled numerical optimum.

2 Review approach and evidence boundaries

This is a focused critical narrative review. Targeted searches combined steel fibre reinforced concrete, zigzag, crimped, hooked, aspect ratio, volume fraction, workability, compressive strength, splitting tensile strength, pull-out and orientation. Sources were located through publisher pages, institutional publication repositories and reference checking. Bibliographic details were checked against DOI metadata and publisher or institutional records. Checking was completed on 5 November 2026. The selected primary literature spans 1991–2025. This range describes the included evidence, not an exhaustive database search window.

Priority was given to experiments or mechanistic studies that explain the relation between steel fibre geometry, dosage and concrete performance. Conventional and high-strength cast concrete provide the main context. Shotcrete, layered concrete and single-fibre pull-out studies are identified separately because their processing or measurement conditions differ. Hybrid natural-fibre composites, polymer-only reinforcement and environmental-exposure studies are outside the central scope. No numerical observation from the accompanying thesis is treated as independently published literature evidence in this review.

The review does not claim systematic retrieval, formal risk-of-bias scoring or meta-analysis. Access to the cited material ranges from full text to publisher abstracts and previews. Numerical designs or results are used only to the extent supported by the accessible record. No pooled effect size or universal dose–response relation is fitted. The evidence tables are an interpretive map, not a ranking of study quality or a claim of complete extraction.

Table 1 Evidence groups and their role in the synthesis

Group	Examples	Role and boundary
Fibre type and fresh mixtures	[1], [2]	Identify shape and processing effects; avoid reducing workability to one geometric index.
Mechanical response	[5], [3], [4], [6], [7], [8], [9]	Compare test-specific properties across defined matrix and fibre conditions.
Distribution and orientation	[10], [11], [12]	Explain why bulk content differs from fibres crossing a fracture plane.
Pull-out and bond	[13]–[15]	Connect fibre geometry with local anchorage and orientation-dependent response.
Post-cracking and application context	[16], [17]	Distinguish energy absorption and layered placement from peak cube or cylinder strength.

3 Fibre geometry and reinforcement mechanisms

3.1 Shape is more than aspect ratio

For a circular fibre, aspect ratio is the ratio of length L to diameter d. Yazıcı et al. [5] investigated hooked-end fibres with aspect ratios of 45, 65 and 80 at three volume fractions. Their design demonstrates how geometry and content can be varied jointly rather than attributing a dosage response to aspect ratio. It does not identify an aspect ratio that must be preferred in every matrix or for every fibre shape.

$$\text{Aspect ratio} = L / d \tag{1}$$

Aspect ratio is a descriptor, not a complete constitutive parameter. It omits end deformation, surface condition, steel strength and casting orientation. For a deformed fibre, the reported length must also have a defined measurement convention. A projected length and a contour length should not be used interchangeably when describing a zigzag or crimped product. The same numerical ratio can therefore represent fibres with different anchorage geometry.

The shape comparisons of Soroushian and Bayasi [1] provide a basis for considering geometry explicitly. A useful zigzag-fibre report should include a photograph or dimensioned drawing, nominal and measured dimensions, and the manufacturer's product designation. A supplier label such as deformed steel fibre does not establish equivalence to the hooked or crimped products in another experiment. Transfer of published findings should be stated as a hypothesis when the geometry differs.

3.2 Anchorage and pull-out

Banthia and Trottier [15] investigated bond–slip mechanisms for deformed steel fibres. Robins et al. [13] examined hooked-fibre pull-out with attention to matrix strength, embedment and orientation. Laranjeira et al. [14] developed a predictive treatment of inclined hooked-fibre pull-out. These studies connect local anchorage with composite response, while also showing why a fibre's action depends on more than the amount of steel added.

A peak-load concrete test does not identify the active microscopic mechanism uniquely. A higher splitting load may be compatible with increased crack bridging, but it does not measure pull-out force, embedment distribution or fibre rupture. A mechanistic claim requires an additional observation that distinguishes competing explanations. For example, examination of fracture surfaces can identify whether fibres pulled out or broke; a controlled pull-out experiment can then isolate local interface behaviour. These measurements should complement, rather than be inferred from, bulk strength.

3.3 Distribution and orientation

Dupont and Vandewalle [10] considered the number of fibres crossing rectangular sections and its relationship with distribution. Laranjeira et al. [12] characterised orientation profiles, and Laranjeira et al. [11] proposed a framework to predict orientation. Together, this work supports distinguishing fibre content in the mixture from the reinforcement present at a particular section. Nominally random mixing does not justify assuming identical orientation in every specimen or structural element.

This distinction has practical consequences for comparing cubes, cylinders and beams. Their boundaries and casting procedures differ. A fibre arrangement formed by placing a mixture into a cylinder may not represent that in a slab or a thin panel. Where the goal is structural transfer, the experiment should document placement direction and compaction and should evaluate the relevant geometry. An observed specimen strength cannot by itself establish a transferable orientation factor.

4 Dosage definitions and workability

4.1 The denominator must be explicit

A fibre content of 1% is incomplete unless its denominator is stated. It can refer to steel volume divided by concrete volume, steel mass divided by cement mass, or another mass basis. These conventions are not interchangeable. Published volume-fraction experiments should be compared with a thesis percentage only after its definition is known. The following definitions provide a consistent reporting basis:

$$\text{Volume fraction } V_f = \text{fibre volume / concrete volume} \quad (2)$$

$$\text{Cement mass fraction } q_c = \text{fibre mass / cement mass} \quad (3)$$

If fibre mass per unit concrete volume and steel density are known, the volume fraction follows by dividing the former by the latter. Conversion from a cement-mass percentage additionally requires cement content per unit concrete volume. Steel specific gravity alone cannot supply that missing quantity. For a deformed product, the metal volume should be determined consistently rather than approximated from an undefined projected diameter.

A commonly useful geometric content index is $V_f(L/d)$, with V_f entered as a fraction rather than a percentage. It is an organising parameter, not a claim that every shape shares one performance curve. If V_f is entered as 1 instead of 0.01, the numerical index changes by a factor of 100. Clear units and conventions therefore matter even when the equation appears simple.

$$\text{Reinforcement index } F = V_f(L/d) \quad (4)$$

4.2 Fresh consistency and placement

Bayasi and Soroushian [2] measured fresh properties using several methods and found effects associated with the fibre reinforcement index and fibre type. Their use of slump, inverted-cone and Vebe measurements illustrates that fresh performance is not exhausted by one consistency number. Holschemacher et al. [9] also considered workability alongside mechanical response in high-strength concrete with different fibre types and quantities.

A practical experiment should distinguish initial consistency from retention and from the ability to achieve compaction in the intended mould. Increasing fibre content changes the solid skeleton as well as the quantity of reinforcement. When extra water is used to restore slump, the matrix is also changed. When a chemical admixture is adjusted, its identity, solids content and dosage basis should be recorded. Either adjustment can be legitimate, but it must appear in the interpretation.

Two comparison strategies are particularly useful. The first holds the available-water ratio, aggregate grading and paste volume as constant as possible and measures the fresh response to fibres. The second targets comparable placement consistency and reports the adjustments needed to achieve it. The first addresses material sensitivity; the second addresses production feasibility. A study should state which strategy it uses instead of combining their conclusions.

Table 2 Controls needed to interpret dosage effects

Comparison	Required information	Interpretive value
Equal nominal matrix	Water ratio, paste volume, grading and fibre addition	Separates a fibre-associated response from a redesigned matrix.
Equal target consistency	Added water, admixture adjustments and mixing sequence	Shows the resources needed for practical placement.

Comparison	Required information	Interpretive value
Equal geometry	Measured fibre shape, length, diameter and strength	Supports dosage comparison without a geometry change.
Equal dosage	A common verified volume or mass basis	Allows a controlled geometry comparison.
Production variability	Independent batches and specimen allocation	Distinguishes repeat testing from repeat production.

5 Mechanical performance and appropriate comparisons

5.1 Compressive strength

Song and Hwang [3] examined several mechanical properties of high-strength concrete with different steel-fibre contents. Thomas and Ramaswamy [4] similarly treated mechanical properties through an experimental and modelling programme. Their relevance is that compressive strength is one outcome in a wider material response. A single favourable percentage should not be used to represent every performance measure.

Ding and Kusterle [6] investigated early-age compressive stress–strain behaviour, separating the loading response from a single peak strength. Bankir and Bikce [8] more recently evaluated static and dynamic mechanical properties with varied aspect ratio and fibre rate. These studies broaden the experimental questions: strength, stiffness and deformation response require their own measurements. They should not be reconstructed from an uninstrumented cube failure load.

For comparisons across studies, the specimen geometry, age, curing and reference mixture must be retained. A fibre mixture tested at 28 days and a control tested at 7 days do not isolate a fibre effect. A cylinder compressive strength and a cube compressive strength should not be pooled as if they were identical observations. If a conversion is used, its source and applicability must be stated.

5.2 Splitting tensile strength

Splitting tensile strength is an indirect response to a specified loading arrangement. Its improvement should be reported relative to the same-age control. Yazıcı et al. [5] included splitting and flexural tests in their geometry–dosage experiment. Nili and Afroughsabet [7] varied water–cement ratio and included mixtures with silica fume as well as steel fibres. Their study cautions against treating a change in matrix composition as merely a change in fibre action.

A comparison between compressive and splitting responses can help identify which measured property changes more strongly in a particular programme. However, a larger relative splitting gain does not establish direct tensile strength, a tensile constitutive law or residual strength after cracking. These are related but distinct measurements. The reference denominator also matters: a large percentage may partly reflect a low control value.

$$\text{Strength change (\%)} = 100 \times (\text{fibre concrete} / \text{matched control} - 1) \quad (5)$$

Equation 5 should be evaluated separately for each property and age. Its uncertainty depends on the variability of both the treatment and the control. If only summary values are available, a descriptive ratio can be calculated, but a standard deviation or significance test cannot be recovered without the underlying observations or equivalent sufficient statistics. The reporting language should match that level of evidence.

5.3 Peak strength is not toughness

Banthia and Trottier [16] investigated toughness characterisation in concrete reinforced with deformed steel fibres. This provides a direct reason to distinguish peak load from energy absorption. A load–deflection or load–crack-opening record contains information that a single failure load does not. A claim about post-cracking resistance needs an appropriate controlled test and measurement range.

The distinction is consequential when choosing a mixture. A composition with a modest peak-strength change may still warrant investigation for post-cracking performance, while a high cube strength does not certify residual capacity. The engineering acceptance criteria should be selected before an optimum dosage is declared. Without those criteria, optimum may mean only the largest number in the available table.

Table 3 Selected primary studies and the comparison they support

Study	Design or focus	Use in interpretation
Yazıcı et al. [5]	Hooked fibres; aspect ratios 45/65/80; volume fractions 0.5/1.0/1.5%	Geometry and dosage can be varied independently.
Song and Hwang [3]	High-strength concrete and multiple strength measures	Keep mechanical outcomes separate.
Thomas and Ramaswamy [4]	Mechanical testing and property models	Models need the population and controls for which they were developed.
Ding and Kusterle [6]	Early-age compressive stress–strain behaviour	Age and deformation response require explicit measurement.
Nili and Afroughsabet [7]	Steel fibres, two water ratios and silica-fume conditions	Additional matrix changes limit attribution to fibres alone.
Robins et al. [13]	Hooked-fibre pull-out; embedment and orientation	Local anchorage depends on the interface configuration.
Bankir and Bikce [8]	Aspect ratio and fibre rate; static and dynamic response	Property-specific testing can be combined with statistical analysis.
Chakravarti and Rajasekhar [17]	Layered concrete with hooked fibres	Layer arrangement is an additional factor, not a uniform-mixture dosage.

6 Transferability to zigzag fibres

Zigzag fibres belong within the broader family of deformed steel reinforcement, but their geometry should be identified directly. Hooked-fibre pull-out models are not automatically zigzag models. The mechanistic studies [13]–[15] offer questions about anchorage and orientation; they do not eliminate the need to measure a different product. The same caution applies to transferring strength gains from high-strength concrete to an ordinary-strength matrix.

The recent layered-concrete investigation of Chakravarti and Rajasekhar [17] illustrates another boundary. Their programme combined hooked fibres with a deliberate arrangement of reinforced and unreinforced layers. It can inform the design of application-specific tests, but does not represent uniformly dispersed short zigzag fibres. The relevant unit of comparison is the complete

material and placement system, not the shared word steel.

For a fixed zigzag geometry, a dosage series can establish the order of the reported responses within the tested range. It cannot establish an optimum aspect ratio because aspect ratio was not varied. Similarly, if only 0%, 1%, 2% and 3% labels are tested, a decrease beyond 3% cannot be claimed. A maximum among observed values is not evidence about unobserved compositions. Confirmation experiments should be designed around the decision that remains unresolved.

7 Proposed framework for future experiments

The following framework is a synthesis for experiment design. First, define the intended use and its required fresh and hardened properties. Second, characterise the matrix and fibre and state the dosage denominator. Third, establish a matched control and record any mixture adjustments. Fourth, vary dosage and geometry through identifiable factors. Fifth, evaluate the results using the measurements actually collected. Finally, confirm the preferred feasible mixture in independent production batches.

A geometry comparison should avoid changing fibre steel strength or matrix composition inadvertently. Where commercial products differ in several characteristics, the experiment should be reported as a product comparison rather than an isolated aspect-ratio test. A dosage experiment should record actual fibre mass, mixture yield and placement losses. That information allows nominal content to be checked against the delivered material.

Table 4 Research gaps and testable follow-up questions

Priority	Question	Suitable evidence
Zigzag geometry	Does shape change response at matched content and matrix?	Dimensioned products, common dosage basis and direct geometry comparison.
Dosage denominator	Are nominal percentages comparable across programmes?	Batch masses, concrete yield and a verified volume conversion.
Fresh performance	Can the mixture be placed consistently?	Repeated consistency measurements and compaction observations.
Marginal benefit	Does an extra dosage increment produce a reproducible gain?	Independent batches, specimen statistics and matched controls.
Post-cracking capacity	Does the chosen mixture retain load after cracking?	Instrumented flexural or tensile response over a defined deformation range.
Scale transfer	Do specimen outcomes persist in the intended element?	Representative casting direction, dimensions and structural tests.

The framework does not prescribe a universal percentage or a new empirical design law. Its purpose is to prevent a change in definition or production from being misread as a material mechanism. It also clarifies when additional testing is necessary. Where the available evidence consists only of summary peak strengths, the next useful work is recovery of specimen records and measurement of variability, not fitting a more flexible model to the same few values.

8 Limitations

The literature selection is purposive, and the accessible records do not provide uniform extraction detail for every study. Publication bias, between-study heterogeneity and pooled effect sizes are not quantified. The review therefore supports qualitative interpretation and experiment design rather than numerical acceptance limits. Its proposed equations are definitions and descriptive comparisons, not calibrated predictive relationships.

The discussion of transfer to zigzag fibres identifies evidence requirements; it does not claim that the cited hooked-fibre studies validate a particular zigzag product. Current code compliance, durability, fire performance, corrosion resistance, lifecycle cost and carbon benefit are not assessed. Those questions require their own sources and measurements.

9 Conclusions

Steel-fibre concrete should be described through the fibre product, dosage basis, matrix and production process together. Geometry comparisons in the literature show why aspect ratio alone does not define fibre action. Local anchorage and orientation help explain the response, but a bulk peak-strength test cannot identify those mechanisms uniquely.

Workability must be evaluated alongside strength because the ability to mix, place and compact the material is part of the experiment. Adjustments to water or admixture should be documented and included in the interpretation. Compressive strength, splitting tensile strength and post-cracking resistance remain separate acceptance questions.

For short zigzag fibres, a fixed-geometry dosage series can identify promising tested treatments but cannot establish an optimal aspect ratio or behaviour beyond the largest dosage. A defensible recommendation requires an explicit dosage denominator, matched controls and independent-batch variability. The most useful next step is a reproducible experiment that couples fresh performance with the mechanical property required by the intended application.

Data availability

No new experimental measurements were generated for this review. Published evidence is identified in the reference list. The reporting framework is a synthesis proposed for evaluating future experiments.

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