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Meta-Analysis of Fiber Impact on Mechanical Properties of Ultra-High Performance Concrete

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Abstract

The purpose of this study was to conduct a meta-analysis that shows the effects of fiber on ultimate compressive ultra-high performance concrete and its tensile strengths. The internet scholarly search engines and ScienceDirect article references were used to illustrate the papers concerning the experimental investigations of mechanical properties of ultra-high strength concrete with and without fiber with clearly, completely and comparative raw data. The normal concrete test results were dismissed from this search. Seven trials were identified based on the adopted inclusion and exclusion criteria above. The meta-analysis based on standardized mean difference was carried out on the basis of a fixed-effects model for the major outcomes of the ultimate compressive and tensile properties of ultra-high performance concrete. A total of 888 test specimens were enrolled in these seven trials. The combined analysis yielded a sign of a significant improvement in ultimate compressive and tensile ultra-high performance concrete strengths with fiber addition of 2% by concrete volume. The summary effect size of ultimate compressive strength was 2.34 while a more improvement in term of tensile strength with effect size of 2.64. By addition fiber of 2% provides a significant benefit in mechanical properties of ultra-high performance concrete.

Keywords:
Meta-analysis; Effect size; Precision; Ultra-high strength concrete; Ultra-high strength fiber reinforced concrete.

Introduction

High-strength concrete (HSC) usually used for concretes whose grade more than 40 MPa. Sometimes they named high-performance concretes if they have other excellent properties. Today, many mills can produce concrete with compressive strength at least 60 MPa and concrete has been made now in laboratories with strength higher than 140 MPa. The latter concrete is named ultra-high-strength concrete (UHSC) or ultra-high-performance concrete (UHPC). To manufacture concrete with strength above 40 MPa, it is necessary to use very

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good work control in term of quality with better materials selection. Generally concrete strength increases by using less water–cement ratios with appropriate admixtures and sound aggregates. If silica fume which is usually ranged from 5% to 30% of the weight of the cement [1] with specific superplasticizer are used, concrete with strength from 40 MPa to 80 MPa can be obtained.

Recently, fiber-reinforced concrete (FRC) become popular and the current research well interested in this type of concrete. Various attempts have recorded that the addition of fibers to normal concrete in quantities from 1% to 2% by volume can improve its some properties. The compressive strength of fiber-reinforced normal concrete is not significantly greater than the one without fiber [2] due to small amount of fibers passed throughout the crack which are do not a valuably increase the strength of the normal concrete. But, the resulting concrete is much tougher, brittleness reduction, ductility increasing with high cracking, fatigue and impact resistance due to energy required to pull the fiber and then to open the crack. The most commonly used material for the fibers is steel and usually the fibers can be hooked at its ends for bond purpose. The improvement obtained in the toughness of the concrete due to adding fibers is dependent on very important parameter which is called "the fibers’ aspect ratio" The fibers' aspect ratio is defined as divided the length of the fiber by its equivalent diameter. 25 up to 150 are the typical aspect ratios used with 100 being about an average value [2]. The demands of the designers for HSC to satisfy the requirement of mega projects became necessary today’s. Due to the progress in concrete technology, ultra-high strength concrete (UHSC) or ultra-high performance concrete (UHPC) is considered a new class of concrete. This concrete is limited with concretes which have characteristics compressive strength higher than 100 MPa. The UHSC or UHPC has property of brittle failure and a limited post crack behavior. The literature proved that when adding fibers to UHSC or UHPC, the brittleness property and post cracking behavior can be improved mush higher relative to normal concrete or even HSC.

Meta-Analysis

The early type of review was named narrative review. Generally the narrative review is built from non-continuous reports which are synthesizing from a continuous set of researches. No actual procedure for collecting the data is providing by this type of a review. In contrast,

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there are two fundamental changes in a systematic review using meta-analysis. The first one is the effect size from individual study used directly. While other change is single statistical synthesis is used to include all the effects. The effect size of each study and its variance must be first known in order to carry out any combined analysis such as meta-analysis. It is easy then to find the weighted mean of these effect sizes [3].

If any given study records mean and standard deviation for under consideration variable. Then the effect size can be usually defined in three different types which are the response ratio, the mean raw difference and the mean standardized difference. Meta–analysis can be performed directly based on the means raw difference if the studies results are recorded on same scale in the experimental. While mean standardized difference might be adopted if different testing laboratory machines were used to get the result in different studies. The standard mean difference on the basis of a fixed-effects model is used in this study as an effective size. The effective size (ES) based on mean difference of two independent groups can be estimated as [4]:

$$ES = \frac{\overline{X}_1 - \overline{X}_2}{S_{within}} \qquad 1$$

where $\overline{X}_1$ and $\overline{X}_2$ are the sample means in the two groups (control group without fiber and the treated group with fiber). S_{within} is the within-groups standard deviation, pooled across groups as [4]:

$$S_{within} = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}} \qquad 2$$

Where n_1 and n_2 are the sample sizes in the control and treated groups respectively. S_1 and S_2 are the standard deviations in the two groups. In spite of, in many cases when the population standard deviations are identical; it dose not necessarily that the sample standard deviations will be the same. It can be obtained a more accurate result by collecting the two sample standard deviation estimates. The variance of ES is given approximately as [4]:

$$V_{ES} = \frac{n_1 + n_2}{n_1 n_2} + \frac{ES^2}{2(n_1 + n_2)} \qquad 3$$

The first term in Eq.3 accounts to uncertainly in the mean difference estimate. The second term reflects uncertainty in the estimate of S_{within}. The standard error of ES is defined as the square root of V_{ES} as:

$$SE_{ES} = \sqrt{V_{ES}} \quad 4$$

If the effect size is assumed normally distributed, then the 95% confidence interval (the lower limit LL and the upper limit UL) can be computed as:

$$LL = ES - 1.96 \times SE_{ES}$$

$$UL = ES + 1.96 \times SE_{ES} \quad 5$$

The forest plot provides a full context for the meta-analysis. The main part of the forest plot is the boxes. Each box is drawn to each study in the overall meta-analysis. The effect size for individual study is represented by the center of each box. While, the inverse of each study's standard variance is equal to the area of individual related box. The inverse of individual study's standard error is proportional to the each related box side. Finally, the confidence interval for each box is proportional to that study's standard error. The summary effect size in any forest plot represents by a diamond shape instead of box. The center of the diamond represents the mean effect size while the width of the diamond depicts its confidence interval.

Attempts and Trials

Different internet research engines especially ScienceDirect, ResearchGate used to collect the required studies that cover the objective of this paper. The inclusion search criteria assumed each study must cover the mechanical properties of UHPC with and without fiber in clear and complete data capable for comparison. Some studies tested the UHPC with different age, different fiber volume fraction and different specimen size. Code practice and nonlinear interpolation techniques is used to adjusted the concrete age, volume fraction of fiber and the specimen size. The meta-analysis was carried out for all studies based on 28 days concrete age, 2% fiber volume fraction and standard cubic specimen for ultimate compressive strength and standard prism for tensile strength. UHPC without fiber was named as control while UHPC with fiber was named simply as treated.

Yu et. al. (2014) [5] investigated the strengths of UHPC with steel fiber of length 13 mm and diameter of 0.2 with dosage of 2% by mixture volume. The total number of tested specimens for both ultimate compressive and flexural strengths was 36 as control and 180 as treated. The UHPC composes of Portland cement, with either high cement content or cement reduced by Limestone or cement reduced by Quartz with superplasticizer type polycarboxylic ether. The average ultimate compressive strength for the control and the treated mixtures are 99.0 MPa (Standard deviation, SD = 6.00) and 135.0 MPa (SD = 10.00) respectively. While, the mean tensile flexural strength for the control and treated mixtures are 16.0 MPa (SD = 2.00) and 23.0 MPa (SD = 2.50).

Abbas et. al. (2015) [6] investigated the mechanical properties of UHPC of various mixtures with varying steel fiber lengths 8, 12 and 16 mm. The fiber content ratios were 1%, 3% and 6% by mixture volume. The total number of tested specimens was 24 as control and 144 as treated. The UHPC composed of Portland cement, silica fume, quartz sand, quartz powder with superplasticizer type polycarboxylate. While the used fiber is Copper coated steel fiber L/d= 40 to 80. The average ultimate compressive strength for the control and the treated mixtures are 134.5 MPa (Standard deviation, SD = 5.67) and 143.3 MPa (SD = 5.74) respectively. While, the mean tensile flexural strength for the control and treated mixtures are 12.4 MPa (SD = 0.42) and 26.0 MPa (SD = 2.95). While, Eldin et. al. (2014) [7] studied also the mechanical properties of UHPC but with varying steel fiber length 30, 50 mm, with dosages 0%, 1%, 2% and 3% by mixture volume. The total number of tested specimens was 36 as control and 108 as treated. The UHPC composed of Portland cement, silica fume, sand with grain size smaller than 0.6, natural crushed basalt graded from 1.18 mm to 10 mm with superplasticizer. The steel fiber with aspect ratios L/d= 30 and 50 was used. The mean ultimate compressive and tensile flexural strengths for the control specimens are 145.0 MPa and 15.7 MPa with standard deviation of 4.23 and 0.36 respectively. The average ultimate compressive strength for the treated mixtures with L/d = 30 and L/d = 50 are 166.0 (SD = 8.93) and 172.0 MPa (SD = 13.07) respectively. While, the mean tensile flexural strength for the treated mixtures with L/d=30 and L/d = 50 are 19.9 (SD =1.83) and 21.7 MPa (SD =1.79) respectively.

Yu et. al. (2015) [8] used hybrid short and long steel straight fiber with 2% volume in the production of UHPC. The total number of tested specimens was 12 as control and 60 as treated. The UHPC composes of ordinary cement, Polycarboxylic superplasticizer, limestone powder and nano-silica in slurry. While the steel fiber is used with L/d = 37.5 to 65. The average ultimate compressive strength for the control and the treated mixtures are 101.0 MPa and 134.3 MPa with SD of 1.52 and 7.98 respectively. While, the mean tensile flexural strength for the control and treated mixtures are 14.2 MPa (SD = 1.81) and 25.8 MPa (SD = 3.00). While, El-Dieb (2009) [9] showed that ultra-high strength concrete could be obtained using local available materials and different volume dosage of steel fiber of 0.8%, 1.2% and 5.2 %. The total number of tested specimens in this study was 15 as control and 45 as treated. The Ultra-high strength concrete composes of ordinary Portland cement, silica fume, coarse aggregate, sand with modified polycarboxylic ether superplasticizer. While the used steel fibers are twisted with a triangular cross-section of L/d = 50. The average ultimate compressive strength for the control and the treated mixtures are 98.5 MPa (SD = 2.59) and 113.7 MPa (SD = 3.50) respectively. While, the mean tensile flexural strength for the control and treated mixtures are 4.7 MPa (SD=3.50) and 10.5 MPa (SD= 0.99) respectively.

Magureanu et. al. (2010) [10] were investigated the physical properties of UHPC with 2% volume of steel fibers. The UHPC subjected to two curing methods (thermal treatment and water curing). The total number of tested specimens was 36 as control for and 36 as treated for both curing methods. The UHPC composes of Portland cement, grey silica fume; very fine sand, coarse aggregates were eliminated with superplasticizer (polymer ether-carboxylate). While the steel fiber is used with L/d = 62.5. The average ultimate compressive strength for the control and the treated mixtures for thermal treatment are 162.0 MPa and 182.0 MPa with standard deviation of 1.12 and 5.4 respectively. While, the average tensile flexural strength for the control and treated mixtures are 13.4 MPa (SD = 1.15) and 25 MPa (SD = 2.30). However, the average ultimate compressive strength for the control and the treated mixtures for water curing are 108.0 MPa (SD = 9.10) and 132.0 MPa (SD = 14.30) respectively. While, the mean tensile flexural strength for the control and treated mixtures are 8.4 MPa (SD =1.60) and 14.3 MPa (SD = 2.60).

Orgass and Klug (2004) [11] investigated the effect of two types of steel fiber. In the first one, they used steel fiber with a short length of high strength. While in the other type, they adopted steel fiber with large length of normal strength. The steel fibers content ratios were 0%, 1% and 2% by mixture volume. The effect of these two types of fiber on the mechanical properties of self compacted reactive powder concrete (SCRPC), reactive powder concrete with normal compacted method (CRPC) and ultra-high performance concrete also with normal compaction (CUHPC) had been studied experimentally. For the SCRPC the total number of tested specimens was 15 as control and 15 as treated. SCRPC consist of ordinary cement under name Portland, quartz powder and silica fume of white color with superplasticizer. Equally mix steel fibers are of both above type were used with L/d= 40 to 80. The average ultimate compressive strength for the control and the treated mixtures are 157.0 MPa with SD = 3.20 and 170.5 MPa with SD = 11.50 respectively. While, the average tensile flexural strength for the control and treated mixtures are 9.3 MPa (SD =0.26) and 16.6 MPa (SD = 3.98). For the CRPC the total number of tested specimens was 21 as control and 42 as treated. CRPC consist of ordinary Portland cement, grey silica fume and quartz powder, without coarse aggregate and with superplasticizer type polycarboxylateether. The used steel fibers CRPC concrete was of long normal strength L/d= 80. The average ultimate compressive strength for the control and the treated mixtures are 132.0 MPa (SD = 9.2) and 145.0 MPa (SD = 10.47) respectively. While, the mean tensile flexural strength for the control and treated mixtures are 10.3 MPa (SD = 0.54) and 15.1 MPa (SD = 1.76). Finally, for the CUHPC the total number of tested specimens was 21 as control and 42 as treated. The CUHPC composed of ordinary Portland cement, grey silica fume, sand in the scale of 0.3 to 0.8 mm of quartz type was used as a fine aggregate and the coarse aggregate was of type basalt splits with particles (1 to 3) and (2 to 5) mm. Finaaly superplasticizer of type polycarboxylateether was added to the mix. While the used steel fibers of long normal strength of L/d = 80. The average ultimate compressive strength for the control and the treated mixtures are 125.0 MPa (SD = 12.49) and 134.0 MPa (SD = 9.10) respectively. While, the mean tensile flexural strength for the control and treated mixtures are 10.0 MPa (SD = 1.29) and 12.2 MPa (SD = 2.50).

Some trials did not match the inclusion criteria or the objective of this research was illustrated in this paragraph also. Habel et. al. (2006) [12] and Kang et. al. (2010) [13] studied the mechanical properties for UHPC with fiber only at several ages but unfortunately the studies done without control data. Chanh (2004) [14] investigated the influence of steel fiber on the mechanical properties of normal concrete only. Kang et. al. (2011) [15] investigated the effect of

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fiber distribution characteristics and direction of placement with steel fiber dosage fixed to 2% by volume of concrete on the flexural tensile strength of UHPC without control specimens. Finally, Hassan et. al. (2012) [16] studied the mechanical properties of UHPC. The data were extracted completely from the paper but the results in term of effective size had a very large deviation from the rest of the matched trials.

The combined analysis is performed in this study based on standardized mean difference for the above trials that satisfy the inclusion objective criteria. The results in term of effect size and weight with forest plot are recorded in Fig.1 and Fig.2. Fig.1 showed the effect of fiber on ultimate compressive ultra-high performance concrete strength with summary effect size of 2.34. While, Fig.2 illustrated the influence of fiber on tensile strength of ultra-high performance concrete with the more value summary effect size which is equal to 2.64.

Study Name	Effect Size	Weight %
Abbas et al, 2015	1.51	19%
Yu et al, 2015	4.40	4%
Yu et al, 2014	3.77	15%
Eldin et al, 2014	2.56	12%
Eldin et al, 2014	2.29	12%
Magureanu et al, 2010	4.56	2%
Magureanu et al, 2010	3.24	3%
El-Dieb, 2009	4.51	5%
Orgass and Klug, 2004	1.48	5%
Orgass and Klug, 2004	1.22	11%
Orgass and Klug, 2004	0.85	12%
Summary	**2.34**	**100%**

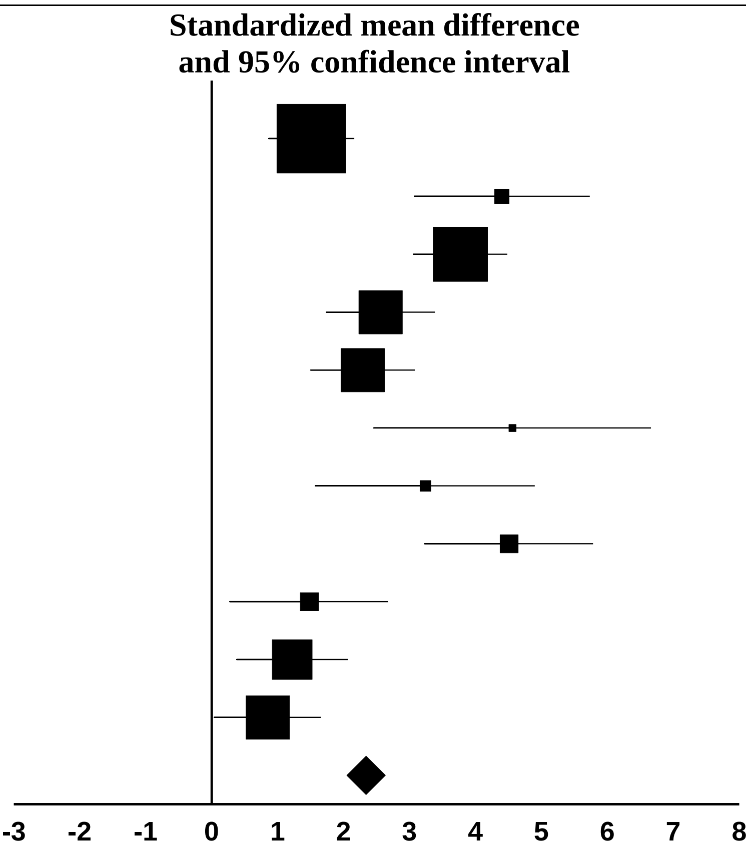

Fig.1: Impact of Fiber on Ultimate Compressive Strength of Ultra-High Performance Concrete

Study Name	Effect Size	Weight %
Abbas et al, 2015	4.90	10%
Yu et al, 2015	3.97	6%
Yu et al, 2014	2.86	24%
Eldin et al, 2014	2.50	7%
Eldin et al, 2014	3.70	5%
Magureanu et al, 2010	6.41	2%
Magureanu et al, 2010	2.59	8%
El-Dieb, 2009	6.43	2%
Orgass and Klug, 2004	2.46	6%
Orgass and Klug, 2004	3.17	9%
Orgass and Klug, 2004	0.97	17%
Summary	**2.64**	**100%**

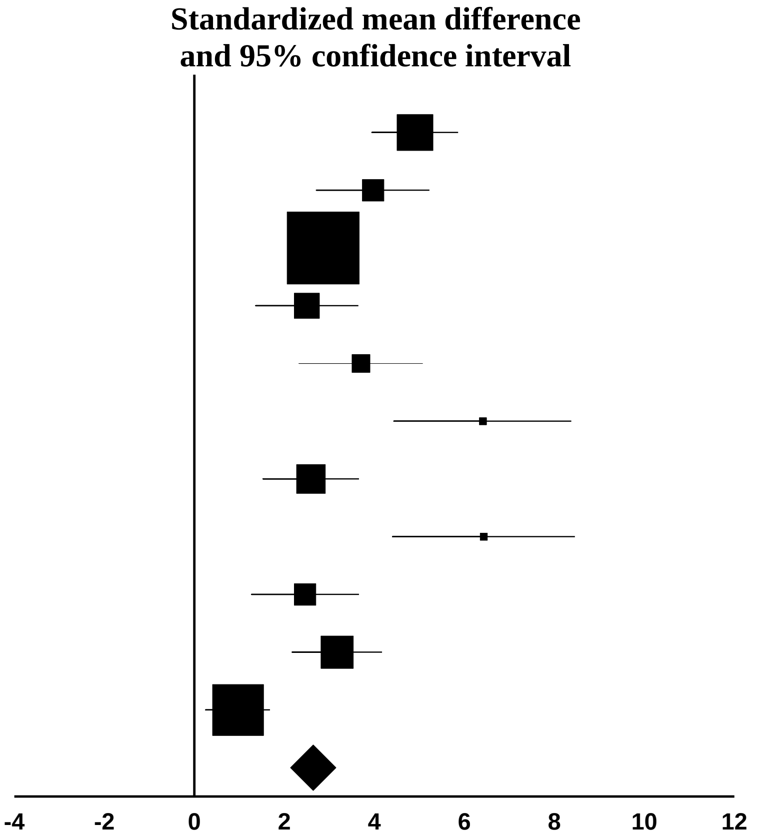

Fig.2: Impact of Fiber on Tensile Strength of Ultra-High Performance Concrete

Conclusions

This systematic review shows significant improvement in ultimate compressive and tensile strengths of ultra-high performance concrete with addition of fiber with a percentage of 2% by concrete volume. The summary effect size of ultimate compressive strength was 2.34 while a more improvement in term of tensile strength with effect size of 2.64. The previous experiments attempts proves that the summary effect size for the ultimate compressive strength and tensile strength of normal concrete with addition of 1% to 2% fiber by concrete volume is approximately approach to zero. Significant improvement in both the ultimate compressive and tensile strengths of concrete with very high performance characteristics with addition of 2% fiber by concrete volume is proved in this study based on strict procedure using meta-analysis. However, the resulting of both normal and ultra-high strength concretes with fiber is much stronger in term of toughness and has excellent property in term of cracking resistance, reducing its brittleness and greater resistance to impact loadings.

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