Hindawi
Advances in Civil Engineering
Volume 2017, Article ID 8078346, 9 pages
https://doi.org/10.1155/2017/8078346

Review Article

State-of-the-Art Report on Fiber-Reinforced Lightweight Aggregate Concrete Masonry

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Received 11 August 2017; Revised 13 October 2017; Accepted 23 October 2017; Published 28 December 2017

Academic Editor: Song Han

Masonry construction is the most widely used building method in the world. Concrete masonry is relatively low in cost due to the vast availability of aggregates used within the production process. These aggregate materials are not always reliable for structural use. One of the principal issues associated with masonry is the brittleness of the unit. When subject to seismic loads, the brittleness of the masonry magnifies. In regions with high seismic activity and unspecified building codes or standards, masonry housing has developed into a death trap for countless individuals. A common approach concerning the issue associated with the brittle characteristic of masonry is addition of steel reinforcement. However, this can be expensive, highly dependent on skillfulness of labor, and particularly dependent on the quality of available steel. A proposed solution presented in this investigation consists of introducing steel fibers to the lightweight aggregate concrete masonry mix. Previous investigations in the field of lightweight aggregate fiber-reinforced concrete have shown an increase in flexural strength, toughness, and ductility. The outcome of this research project provides invaluable data for the production of a ductile masonry unit capable of withstanding seismic loads for prolonged periods.

1. Introduction

The earliest application of lightweight aggregate concrete dates back to the Roman Empire. Lightweight aggregate concrete was the primary manufactured material, using Greek or Italian pumice aggregates mixed with limestone paste. Today, modern lightweight aggregate concrete consists of lightweight aggregate held together by a paste consisting of Portland cement and water [1, 2]. Fiber has been used as a reinforcing material throughout history in the form of mudbricks containing straws, horsehairs, and corresponding natural fibers [3, 4]. Lightweight aggregate fiber-reinforced concrete is a relatively new material [5]. Although lightweight concrete and fibers have been previously employed in construction, their use in modern days dates back to the second half of the nineteenth century. However, it was not until later in the 20th century that the usage and detailed study of properties associated with lightweight aggregate concrete became more significant. This new understanding of the behavior of fiber-reinforced concrete and crack propagation paved the way for the development of new technology. Stronger and lighter concrete sections permitted reductions in the cost of manufacturing, transportation, and foundation design. One of the latest fields affected by the development of lightweight aggregate fiber-reinforced concrete includes the seismic strength of structures.

2. Literature Review

2.1. Lightweight Aggregate Fiber-Reinforced Concrete versus Lightweight Aggregate Concrete. For countless years, lightweight aggregate concrete (LWAC) was utilized for aesthetical or insulation purposes only. This was because of one of the main disadvantages found in both normal and high-strength lightweight concretes: low tensile-to-compressive strength ratio, low flexural strength, low fracture toughness, high brittleness, and large shrinkage [6]. Furthermore, lightweight aggregate concrete is brittle in nature, and when subjected to external loading, a sudden failure under stress occurs. The addition of fibers, however, will allow overcoming the issue associated with the brittleness of the material. The incorporation of fibers into a brittle cement matrix serves to increase the fracture toughness of the composite, through the crack-arresting process, and increase the tensile and flexural strengths. Lightweight aggregate fiber-reinforced concrete would fail only if fibers break or are drawn out of the cement matrix due to tensile forces. The strength mechanics of fiber-reinforced concrete and mortar, extending from the elastic precrack state to the partially plastic postcracked state, is a continuing research topic [7].

2.2. Lightweight Aggregates and Fiber Types

2.2.1. Lightweight Aggregate. Lightweight aggregates are the most important components in the production of lightweight aggregate concrete, with relatively low particle density due to their cellular pore system. Heating certain raw materials, particularly clays, develops the cellular structure within the particles by incipient fusion. At this temperature, gasses are evolved within the pyroclastic mass causing expansion that retains a particular shape upon cooling. This fast cooling creates voids or pores that reduce the total weight of the aggregate. Strong aggregates have pore sizes ranging from 5 to 300 μm. The American Concrete Institute (ACI 213 Committee 2005) provides a detailed report on the characteristics of lightweight aggregate concrete [8].

Two primary sources of lightweight aggregates exist: natural and manufactured. Natural lightweight aggregates like pumice, a froth-like volcanic rock, occur when lava expelled to the air from a volcanic source cools at a relatively fast rate [9]. The most widely used synthetic lightweight aggregate is called expanded clay. Manufacturing of expanded clay consists of heating the clay particles in a rotatory kiln. The term "expanded clay" is commonly used to describe the three main materials used for the fabrication of artificial lightweight aggregates: shale, clay, and slate. Campione et al. stated that the experimental results from the tests performed on lightweight fiber-reinforced concrete show improvements within the application of expanded shale aggregate as oppose to the use of pumice stone. Nonetheless, pumice stone performance was also desirable due to its relatively low cost and suitability in various regions, including seismic areas [9].

One alternative to these expanded clay aggregates is the utilization of lightweight waste materials. This results in the reduction of the overall cost of construction as well as solid waste. One such material is the oil palm shells (OPSs) or palm kernel shells (PKSs), a material available in vast quantities within tropical regions. In the past, some experiments of OPS lightweight aggregate concrete have produced concrete with a grade of 20–50. The compressive strength at 28 days of the OPS concrete varies between 20 and 24 MPa [10].

2.2.2. Fiber Reinforcement. Fiber reinforcement can substantially increase the energy absorption and impact strength of concrete, resulting in improvements within ductility, tensile-to-compression strength ratio, seismic behavior and earthquake resistance, resistance to cracking, and fracture toughness [11].

ACE Committee 544 defines steel fibers as "a short, discrete length of steel having an aspect ratio (length/diameter) from about 20 to 100, with any cross section, and that is sufficiently small and randomly dispersed in an unhardened concrete mixture using usual mixing procedures" [12].

ASTM 820 provides calcification of fiber as follows [13]:

(i) Type I—Cold-drawn wire
(ii) Type II—Cut sheet
(iii) Type III—Melt-extracted
(iv) Type IV—other fibers

Currently, there are many types of reinforcing fibers that can be used in the production of LWAFRC including

(i) steel,
(ii) glass,
(iii) polypropylene,
(iv) natural.

More information about other types of fiber reinforcement can be found in ACI 544 Chapter 2 [12].

Natural fibers exhibit many advantageous properties as reinforcement for composites, especially significant reductions in costs and thermal conductivity. The use of natural fibers could facilitate the reduction and conservation of energy and thereby protect the environment. The principal sources for natural fibers come from coconut husk, sisal, sugarcane bagasse, bamboo, jute, wood, akwara, elephant grass, water reed, plantain and musamba, and cellulose fibers [14]. The disadvantage of adding natural fibers to the concrete mix is reductions in workability due to high amount of fibers leading to a high volume of entrapped air. Similarly, the inclusion of palm fiber results in obtaining a higher density at 0.8% fiber volume. This increment in fibers provided the optimum fiber volume percentage for the mix in which small amount of air bubbles are present. An excessive quantity of the fiber at 1% or more leads to a reduction in bonding strength and disintegration [14].

In summary, fibers improve the ductility of concrete and avoid congestion of secondary reinforcement [15]. The inclusion of fibers develops a more homogeneous and isotropic mixture, transforming the concrete from brittle to a more ductile material. In fact, previous investigations have shown that the unit weight of concrete increases with increasing fiber ratios [16].

2.2.3. Applications. The added fibers can be used as a substitution for the required transverse reinforcement, where large quantities of steel confining reinforcement are needed. The use of fibers can reduce both the weight and cost of structures. This reduction in weight and increase in material strength are useful where seismic codes require higher ductility performance [17].

The brittle nature of lightweight aggregate concrete leads to sudden and precipitated failure. Therefore, adding fiber reinforcement improves the ductility of the lightweight concrete or normal-weight high-strength concrete. Combining lightweight concrete with conventional steel reinforcement and steel or polypropylene fibers reduces the brittleness in the lightweight concrete. Addition of fibers to lightweight aggregate concrete increases the peak and residual frictional stresses. Furthermore, fiber reinforcement may prevent congestion when additional steel reinforcement is required to provide ductility. The main purpose of using lightweight aggregate fiber-reinforced concrete in seismic zones is to improve the seismic behavior of the structures [9, 17, 18]. Moreover, its lightweight characteristic makes this concrete useful in reducing the dead load on high-rise buildings, slabs, and joists, permitting a direct reduction in the foundation size, especially in soils with low bearing capacity [17]. In fact, the lightweight and higher ductility of lightweight aggregate fiber-reinforced concrete make structural members such as marine structures, slabs, joists, bridge girders, and bridge decks both desirable and cost efficient [19]. In addition, lightweight aggregate fiber-reinforced concrete is increasingly being used in precast concrete structures, providing higher strength members and facilitating transportation. The addition of fibers to a concrete mix improves the engineering characteristics of the concrete, for example, ductility, impact strength, and toughness [18]. Properly designed nonstructural fiber-reinforced ultra-lightweight concrete can be easily cut, sawed, and nailed like wood for decorative or insulation purposes [20].

The applications of a lightweight aggregate fiber-reinforced concrete mix vary depending on the required strength, workability, cost, and feasibility. The primary use of fiber-reinforced concrete is to improve tensile strength, the behavior of earthquake resistance, cracking resistance, and fracture toughness [6]. The main purpose of using lightweight aggregate fiber-reinforced concrete in seismic zones is to improve the ductility behavior of the structures under a seismic load. The brittle nature of lightweight aggregate concrete leads to sudden and precipitated failure, and adding reinforcement increases the ductility of the lightweight aggregate fiber-reinforced concrete.

3. Lightweight Aggregate Fiber-Reinforced Concrete (LWAFRC)

3.1. Introduction. The lightweight aggregate fiber-reinforced concrete production consists of the combination of Portland cement, lightweight aggregates such as pumice or expanded manmade clays, steel fibers, water, and other chemicals used to enhance workability and other mechanical properties. The addition of fibers to the concrete mix improves the engineering characteristics of the concrete: ductility, impact strength, and toughness [16, 18].

3.2. Physical Properties. The physical properties of lightweight aggregate fiber-reinforced concrete mainly depend on the characteristics of the aggregates, in particular, the density, fiber strength, and fiber-cement bond. Any increase in the mentioned components will affect the final product strength, workability, ductility, density, and physical appearance. In fact, lightweight concrete requires large amounts of transverse reinforcement steel due to its brittle nature [17]. The strength of the material increases with the use of expanded shale aggregates, while the natural pumice aggregate showed no substantial increase in strength. Nonetheless, pumice stone performance was acceptable in some cases, making this material suitable for regions of seismic activity due to its low cost [9].

3.2.1. Compressive Strength. The failure mode for lightweight aggregate fiber-reinforced concrete matrices depends mostly on the aggregate and not on the cement paste. The main parameters in the experimental compressive strength test include volume percentage of fibers, the type and the volumetric ratio of transverse steel reinforcement, the shape of the specimen (whether a prism, cube, or cylinder), and the length of the specimen. Furthermore, the main parameters affecting the test results include frictional restraints between the load platens, the specimens, and the allowable rotations of the loading platens prior to and during the test. The loading platens should be fixed against rotation once a significant load is applied. Often, capping of specimen ends is used to ensure plane and parallel ends [17].

The addition of fibers increases the maximum compressive strength of LWAFRC expanded clay by 30%. Concrete made of pumice stones with the same dimension and size showed no significant increment in compressive strength. This low strength resulted from the fiber-matrix bond mechanism in concrete and the low strength of the aggregate. This bonding depends principally on the quality of the cement mortar and the fiber properties. Higher strength concrete provides better fiber-matrix interface bonding. Moreover, hooked-end steel fibers influence the compressive strength of concrete [9].

For high-strength LWAFRC, the fibers did not significantly contribute to the compressive strength [21]. In addition, there was no significant increase in the compressive strength of the hardened lightweight self-compacting concrete due to the addition of polypropylene fibers [22]. Steel fibers have a significant effect on energy absorption. As a result, they have a significant impact on the compressive toughness in lightweight aggregate fiber-reinforced concrete since the descending part of the strain-stress curve depends on the addition of fibers [18].

3.2.2. Flexural Strength. Gao et al. indicated the following improvement areas due to the addition of fibers to lightweight high-strength concrete [6]:

(i) Flexural strength: the fracture process of steel fiber-reinforced concrete consists of progressive debonding of fiber, during which slow crack propagation occurs. Final failure occurs due to unstable crack propagation when the fiber pulls out, and the interfacial shear stress reaches the ultimate bond strength. After mix cracks, fiber will carry the load that the concrete took before cracking by the interfacial bond between fiber and matrix.

(ii) Flexural Load: the deflection corresponding to the ultimate load increases with the increase of fiber volume fraction and aspect ratio, and descending branch of the flexural load-deflection curves decreases gently after reaching the maximum load for the fiber volume fraction and aspect ratio.

(iii) Flexural Toughness: cracks first occur in lightweight aggregate concrete rather than in the cement paste under load. In general, fibers serving as crack arrest or barriers increase the tortuosity of an advancing crack. Therefore, the addition of steel fibers to concrete effectively increases the postcracking behavior of steel fiber-reinforced high-strength lightweight concrete.

For concrete mixes with higher fiber steel ratio, 1–2%, strain hardening was observed, and consequently, there is an increase in maximum strain corresponding to failure. At failure, fibers ensure high levels of deformation without a significant reduction in the bearing capacity. For flexural strength, addition of fibers resulted in slow crack propagation and progressive debonding of fibers at high levels of postpeak stress [9].

The increase in flexural strength due to the addition of fibers in lightweight concrete is 91%, 182%, and 260% relative to the increase in specimen size. As stated previously, fiber reinforcement enhances compressive and tensile strength as well as fracture energy absorption, largely improving flexural strength for lightweight aggregate concrete [11].

3.2.3. Splitting Tensile Strength. Cylinder splitting tensile strength increased for lightweight aggregate fiber-reinforced concrete through the addition of steel fibers. Cylinder splitting tensile strength of lightweight aggregate fiber-reinforced concrete is about twice as high as that of plain concrete and lightweight concrete. Specimens with diameter sizes varying from 76, 100, 150, and 200 mm increased in splitting tensile strength of 134%, 33%, 12%, and 0%, respectively, for normal concrete and 127%, 165%, 44%, and 29% for lightweight concrete, respectively [11]. Fiber reinforcement significantly increases the tensile strength of lightweight aggregate concrete [21].

3.2.4. Shear Strength. The addition of steel fiber improves the ductility and energy absorption that causes ductile shear failure. The presence of fibers reduces all deformations including deflection, slab rotation, concrete strain, and steel strain at all stages of loading. However, the effects of fibers are only apparent after the first cracking occurs. Most of the research conducted in the area of shear strength of fiber-reinforced concrete belongs to the slab-column mechanisms. Fibers delay the formation of inclined shear cracking in slab-column connections. As a result, the service load on the lightweight fiber-reinforced concrete slab is increased from 15 to 40%, depending on the serviceability criterion. One of the significant contributions of the fibers in slabs is the elimination of the failing brittle nature of the slab. This process created a failure surface that was very irregular. The fracture surfaces in fiber-reinforced concrete were similar to those in plain concrete slab-column connections. However, the punching perimeter was much larger, resulting in a decrease in the angle of the surface of a maximum of 3° [23].

The major increase in strength of a lightweight concrete mix is a result of a combination of fibers with conventional reinforcement. Fibers act as bridging agents between the inclined cracks produced by the local tensile forces when the strength of concrete around the stirrups surpasses the actual strength for the concrete. This phenomenon increases the shear strength of concrete enclosed between two consecutive stirrups [15].

3.2.5. Modulus of Elasticity. Elastic properties of the aggregate have a substantial influence on Young's modulus. This effect occurs mainly because of the bond existing between the aggregate particles and the cementing material. Young's modulus of elasticity for composite materials such as lightweight aggregate fiber-reinforced concrete can be measured using eight models [24].

(i) Parallel phase model:

$$E_{\mathrm{c}} = E_{\mathrm{m}}V_{\mathrm{m}} + E_{\mathrm{p}}V_{\mathrm{p}}. \tag{1}$$

(ii) Series phase model:

$$\frac{1}{E_{\mathrm{c}}} = \frac{V_{\mathrm{m}}}{E_{\mathrm{m}}} + \frac{V_{\mathrm{p}}}{E_{\mathrm{p}}}. \tag{2}$$

(iii) Dispersed phase (Maxwell) model:

$$E_{\mathrm{c}} = E_{\mathrm{m}}\left[\frac{1 + 2V_{\mathrm{p}}(\alpha-1)/(\alpha+2)}{1 - V_{\mathrm{p}}(\alpha-1)/(\alpha+2)}\right]. \tag{3}$$

(iv) Hirsch–Dougill model:

$$\frac{1}{E_{\mathrm{c}}} = \frac{1}{2}\left[\frac{1}{E_{\mathrm{c,PARALLEL}}} + \frac{1}{E_{\mathrm{c,SERIES}}}\right]. \tag{4}$$

(v) Popovics model:

$$E_{\mathrm{c}} = \frac{1}{2}\left[E_{\mathrm{c,PARALLEL}} + E_{\mathrm{c,SERIES}}\right]. \tag{5}$$

(vi) Counto model:

$$\frac{1}{E_{\mathrm{c}}} = \frac{1-\sqrt{V_{\mathrm{p}}}}{E_{\mathrm{c}}} + \left[\frac{1-\sqrt{V_{\mathrm{p}}}}{\sqrt{V_{\mathrm{p}}}}E_{\mathrm{m}} + E_{\mathrm{p}}\right]. \tag{6}$$

(vii) Hashin–Hansen model:

$$E_{\mathrm{c}} = E_{\mathrm{m}}\left[\frac{(E_{\mathrm{m}} + E_{\mathrm{p}}) + (E_{\mathrm{p}} - E_{\mathrm{m}})V_{\mathrm{p}}}{(E_{\mathrm{m}} + E_{\mathrm{p}}) + (E_{\mathrm{p}} - E_{\mathrm{m}})V_{\mathrm{p}}}\right], \tag{7}$$

(viii) Bache and Nepper-Christensen model:

$$E_{\mathrm{c}} = E_{\mathrm{m}}^{V_{\mathrm{m}}}E_{\mathrm{p}}^{V_{\mathrm{p}}}. \tag{8}$$

For lightweight aggregates made of air entered, the equation for modulus of elasticity of fiber-aerated lightweight concrete is

$$E_{\mathrm{fc}} = 1.259192\left(1 - e^{-0.8134E_{c}}\right), \tag{9}$$

with $r^2 = 0.94$ [25].

For a composite material, Kurugol et al. stated that the Hashin–Hansen model results are very similar to the experimental results. As a result, the model is better for predicting the modulus of elasticity. Likewise, the Counto and Maxwell models predict that Young's modulus for a composite material and give desired results. For the parallel phase model, Kurugol et al. stated that this model predicts acceptable results at low aggregate volume fractions, even though for high aggregate volumes this model overestimates the modulus of elasticity. However, this model is accepted and useful since it provides a simple linear expression [24].

Balaguru and Foden reported that by increasing the fiber volume ratio in the mixture, the modulus of elasticity is enhanced by approximately 30%. Furthermore, by replacing the lightweight fine aggregate with sand, the modulus of elasticity is also expected to increase. As a result, fiber-reinforced concrete exhibits ductility by the addition of coarse lightweight aggregate and fibers [26].

3.2.6. Density of Lightweight Aggregate Fiber-Reinforced Concrete. Due to the brittle nature of the lightweight aggregate concrete, the density of the lightweight concrete depends on the amount and density of the aggregate used. Utilizing aggregates with higher density has shown to improve the strength of the concrete significantly [9]. Structural lightweight aggregate fiber-reinforced concrete is 20–30% lighter than conventional concrete. In this respect, the term "lightweight" is relative. Lightweight aggregate fiber-reinforced concrete bulk densities vary from 800 to 1400 kg/m^3 (50 to 87 lb/ft^3) [20]. The unit weight of concrete decreased with the addition of lightweight aggregates and increased with the addition of fibers [16].

3.2.7. Workability. Lightweight aggregates show two particular characteristics due to their lightness and inclusion of inner voids that can retain water and cause the aggregate to float during the mixing process. These phenomena result in the decline in the workability of the concrete mix. Similarly, fiber entangles together forming a network structure in the concrete mixture that restrains segregation of lightweight aggregates. In addition, the length of the fibers requires more cement paste to wrap around the fiber, influencing the viscosity of the concrete mix affecting the slump. Polypropylene fibers reduced the slump by about 20%, whereas steel fibers reduced the slump by 54%. This is due to the holding effects of the fibers [18, 27].

Workability characteristics of steel fiber-reinforced concrete are complex; shapes of fibers, aspect ratio, and volume fraction are the most important factors affecting the workability. The fiber-reinforced concrete mixes were less workable than mixtures without fibers. The V-funnel test results for plain concrete ranged from 15 to 20 seconds and 35 to 120 seconds for the fiber concrete. The fiber-reinforced concrete mixes with plain fibers show the best compatibility followed by mix with paddle fibers. Mixes with cramped and hooked fibers show less compatibility than those with straight fibers. In fact, hooked fibers require the highest energy compaction. Therefore, the compact ability of lightweight aggregate fiber-reinforced concrete mixes depends on the shape and surface area of the fibers. The compact ability of fiber-reinforced concrete decreases as the design strength increases and decreases as their aspect ratio increases [28].

The presence of polypropylene fibers significantly reduces the slump flow of concrete and increases the time of the V-funnel tests. In the same manner, increasing the amount of the fiber volume ratio reduces the filling height of the U-box test [22].

3.2.8. Drying Shrinkage. It is important to take into consideration the properties of the lightweight aggregate concrete if a prediction model for ultimate shrinkage is to be applied. Lightweight aggregate concrete made with sintered fly ash aggregates displays a long-term drying shrinkage that was nearly twice the value for normal concrete. This drying shrinkage seems to be a result of the high volumetric value of fly ash paste content. As the modulus of elasticity of concrete decreases, the shrinkage value is increased. For normal-weight concrete, a modulus of elasticity of 35 GPa (5076.3 ksi) and ultimate shrinkage value of about 500 microstrains are expected. For lightweight aggregate fiber-reinforced concrete, the expected shrinkage value was around 1000 microstrains and a modulus of elasticity was of 21 GPa (3045 ksi) [21].

The addition of fiber to the concrete mix did not reduce shrinkage at an early state of setting. However, as the concrete cures, the increase in age showed that fibers restrained shrinkage. A higher tensile strength alongside a low modulus of elasticity is believed to be effective in reducing shrinkage cracking. For lightweight aggregate fiber-reinforced concrete, mixes containing carbon fiber combinations produce the greatest reduction of shrinkage [27]. Also, the use of carbon steel fiber combination in lightweight concrete mixtures showed lower brittleness of the concrete as well as a reduction of shrinkage [22].

3.2.9. Fiber-Cement Bond. When the concrete reaches its maximum load, and the first cracks appear, the fibers bridge the inclined cracks that form when overcoming the local concrete tensile strength. The strength of the bridging mechanism will depend on the strength of the fiber or the capacity of the bond between the fiber and the concrete paste. Fibers also increase the shear strength of the concrete enclosed between two section heaves. The results showed that if the anchorage length increases, the extraction forces of longitudinal fibers will also increase. The addition of fibers ensures steel yielding that guarantees a better behavior. For cyclic loading, experimental results show that the highest degradation occurs at the first cycle. This phenomenon is caused in part because the concrete around the rebar is locally crushed in compression reducing the bond strength [15].

A substantial amount of fiber volume guarantees the proper bridging connection between fibers and the concrete paste. The required amount of fibers needed is called critical fiber volume. High frictional bond strength and frictional surface depend on the amount and the physical properties of the fibers. The relationship between fiber volume fraction and composite energy absorption can be given by

$$V_{\mathrm{f}}^{\mathrm{cr}} = \frac{12G_{\mathrm{tip}}}{g\tau^2 L_{\mathrm{f}}} E_{\mathrm{f}} \left(\frac{d_{\mathrm{f}}}{d_{\mathrm{f}}}\right)^2 (1 + \eta), \tag{10}$$

where G_{tip} is the composite energy absorption at crack tip, τ is the frictional bond strength, L_{f} is the fiber length, d_{f} is fiber diameter, and

$$\eta = \frac{V_{\mathrm{f}} E_{\mathrm{f}}}{(1 - V_{\mathrm{f}}) E_{\mathrm{m}}}, \tag{11}$$

where V_{f} and E_{f} are the fiber volume fraction and elasticity modulus of fiber, respectively [29].

3.2.10. Ductility. Ductility is defined as the characteristic of a material to withstand plastic deformation while being loaded beyond peak loads. In addition, ductility may be defined based on bending and compressive resistance. As a primary characteristic of a ductile material, large deformation occurs prior to fracture. In the same way, energy absorption is defined as the area under the load-deflection curve.

Incorporating lightweight aggregates to the concrete mix decreases the ductility of the concrete and at the same time increases the brittleness of the material. The shear and flexural definition of ductility index μ consist of the ratio of the area of the load-deflection response. Shear ductility should only be measured on shear deformation [19].

For lightweight aggregate fiber-reinforced concrete, ductility results from enforced crack resistance due to the fiber bridging concrete layers. Pseudostrain hardening, or multiple cracking in fiber-reinforced composites, occurs with the following sequence: first microcracks appear, and then the concrete matrix transferred the load to the fibers. Consequently, the fibers perform a bridge connection and transfer the load back to the concrete through the interface bond. The load builds up again in the matrix forming another parallel crack. The fibers and the concrete matrix repeat this process until multiple cracking takes place. Eventually, the fibers pull out or break causing total failure of the concrete specimen. The fiber volume fraction of 1.5% or higher achieved strain hardening faster than lower fiber volume fractions. By the addition of 10–20% fly ash and silica-fume cement substitutes, the ductility and flexural strength of lightweight fiber-reinforced concrete are improved. This yields an increment of 50–150% flexural displacement (ductility) at ultimate load [29].

Düzgün et al. concluded that the addition of fibers to the concrete mixes increases the strain and peak stress of the specimens. In the same way, the strain capacity and deformation capability increase greatly as the volume of fibers were increased from 0% to 1.5%. This increase in stress defines the descending portion of the stress-strain curve [16]. Theodorakopoulos and Swamy stated that the addition of fibers to a brittle lightweight concrete generates an increase in ductility of 125%–158% and an increase in energy absorption of 216%–237% [23]. Libre et al. provided a complete work on the ductility of lightweight aggregate fiber-reinforced concrete based on the flexural strength of this material. Specimens tested for flexural strength contained a combination of steel and polypropylene fibers at 0%, 0.5%, and 1% fiber volume. The mix composed of 1% steel fibers and 0.4% polypropylene fibers yield a flexural strength of 7.3 MPa (1058.8 psi), the prepeak energy of 11,920 N mm, and the total energy of 71,112 N mm [18]. Gao et al. worked with high-strength lightweight aggregate fiber-reinforced concrete and observed that the deflection curve is greatly affected by the introduction of steel fibers; it increases with the increase of fiber volume fraction and aspect ratio. In fact, the result showed that plain concrete reached a peak load of 20 kN (4.5 kip) and a deflection of approximately 0.2 mm (0.079 inch). The deflection for a lightweight aggregate fiber-reinforced concrete with a fiber volume fraction of 2% and aspect ratio of 70 reached a peak load of 40 kN (8.99 kip) and a measure deflection of 2.0 mm (0.079 inch) [6].

Arisoy and Wu revised the effects that the lightweight aggregate concrete has on ductility at a constant fiber volume of 1.5%. Ductility increases when lightweight aggregate content is between 40 and 60% of the specimen mix. However, the concrete mix with less than 20% lightweight aggregate showed good ductility. Meanwhile, high volumes of lightweight aggregate concrete resulted in a weak matrix and poor fiber distribution yielding premature failure of the specimens [29].

3.2.11. Toughness Index. Toughness is an important characteristic of fiber-reinforced concrete. Fibers increase their energy-absorbing capability and are more suitable for use in structures subjected to impact and earthquake loads [25, 27]. The toughness definition consists of the ratio of the amount of energy needed to cause a deflection of a specific amount and is expressed as a multiple of the first crack deflection. The toughness is calculated based on the load-deflection behavior of a 100 mm × 1000 mm × 360 mm prism tested under a four-point load stated on ASTM C1018 procedure [30].

The increase of fiber content will yield an increase in the toughness index and postcrack resistance, and lightweight aggregate fiber-reinforced concrete beams can sustain large loads and greater deflections, indicating strain hardening. Fibers with a length of 50 mm (2 inch) show the best improvement of toughness. Evaluation of toughness behavior depends on the values I_{50} and I_{100}.

$$I_5 = \frac{\text{Area under load deflection curve up to } 3\delta}{\text{Area under load deflection curve up to } \delta}. \tag{12}$$

The calculation of these values depends on the load-deflection curve and properly measured small increments. The toughness index magnitude for lightweight aggregate fiber-reinforced concrete is very similar to that magnitude for normal weight concrete of the same strength [26].

Lightweight aggregate fiber-reinforced concrete toughness indexes are not sensitive to specimen size. For high-strength LWAFRC, postpeak loads drop at a faster rate than normal-strength LWAFRC. This change in toughness index indicates that to achieve similar ductility for high strength and low strength, lightweight concrete requires an increase in fiber volume fraction or the addition of fibers with higher strength and hook end [11].

3.3. Preparation Technologies

3.3.1. Scope. The main purpose of the utilization and production of LWAFRC is to provide a lightweight material capable of withstanding greater loads but reducing member size. In order to achieve the required ductile capacity, a very strict material proportion must be followed. The most common manner to design a LWAFRC mixture is to follow ACI 213 in combination with ACI 554 and the experimental research work previously approved by ACI [8, 12].

3.3.2. Mixture Proportion Criteria. Laboratory experimental results show that fluidity of concrete is reduced by the addition of fibers; this concludes that slump test does not provide an accurate evaluation of workability of fresh concrete. Polypropylene fibers show lower effect on workability of fresh concrete, while for steel fibers the effect was higher. The traditional slump test fails to evaluate workability of fiber-reinforced concrete; therefore, it is recommended to utilize the inverted slump cone test for the evaluation of workability of FRC using standardized test ASTM C995 [31].

3.3.3. Materials. The materials utilized in the production of lightweight aggregate fiber-reinforced concrete consist of the following:

(i) Portland cement type II or higher and/or fly ash
(ii) Lightweight aggregates (expanded clay or natural) and normal weight aggregates (sand and fine gravel)
(iii) Fibers (steel, polypropylene, glass, and natural)
(iv) Plasticizers

3.4. Theoretical Modeling. For lightweight aggregate fiber-reinforced concrete, the procedures followed in order to measure and analyze its mechanical properties are very similar to those utilized for normal-weight concrete. The main variation occurs in the workability and modulus of elasticity calculations.

3.5. Design Considerations. In order to design a member made of LWAFRC, the procedures in ACI 544.R [12] must be followed, including the mix selection, placing, finishing, and quality control procedures. While some training is necessary, the equipment used for normal concrete can be used in the production of LWAFRC.

3.6. Applications. The brittle nature of lightweight aggregate concrete leads to sudden and precipitated failure. Therefore, adding fiber reinforcement improves ductility of lightweight concrete or normal-weight high-strength concrete when combined with conventional steel reinforcement and reduces the characteristic brittleness of these materials. The addition of fibers to lightweight aggregate concrete increases the peak and residual frictional stresses. Furthermore, fiber reinforcement may prevent congestion when additional reinforcement is required to provide ductility. The main purpose of using lightweight aggregate fiber-reinforced concrete in seismic zones is to improve the seismic behavior of the structures [9, 17, 18]. Moreover, the lightweight reduced the dead load on buildings supported by low bearing capacity soil [17]. Also, the low weight and higher ductility of LWAFRC make structural members such as marine structures, slabs, joist, bridge girders, and bridge decks very desirable and cost efficient [19]. In addition, LWAFRC is increasingly being used in precast concrete structures, providing higher strength members and facilitating its transportation. Therefore, the addition of fibers is important to improve the engineering characteristics of the concrete, for example, ductility, impact strength, and toughness [18].

Properly designed nonstructural fiber-reinforced ultralightweight concrete can be easily cut, sawed, and nailed like wood for decorative or insulation purposes [20].

The application of a LWAFRC mix varies depending on the required strength and workability. They are mainly viewed in improvements in the tensile/compression ratio, behavior of earthquake resistance, resistance to cracking, and fracture toughness [6]. The main purpose of using lightweight aggregate fiber-reinforced concrete in seismic zones is to improve the behavior of the structures. The brittle nature of the lightweight aggregate leads to sudden and precipitated failure.

4. Research Needs

The following items list important research needs in the area of LWAFRCM:

(i) Further studies need to be conducted on the bonding behavior of fibers and cement paste.
(ii) More research is needed in order to optimize the mixture proportions and examine the effects of hybrid steel and polypropylene fibers on other properties of pumice lightweight aggregate concrete such as shrinkage, creep, durability parameters, and fire resistance.
(iii) Studies on the effect of hybrid fiber mechanical properties of LWAC are warranted based on recent advancement in this area. Thus, more research is needed in order to optimize the mixture proportions and examine the effects of hybrid steel and polypropylene fibers on other properties of pumice lightweight aggregate concrete such as shrinkage, creep, durability parameters, and fire resistance.
(vi) More studies are required to investigate the effects of shear forces on LWAFRCM.

5. ASTM Standards [31–44]

ASTM C39: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.

ASTM C78: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).

ASTM C192: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory.

ASTM C330: Specification for Lightweight Aggregate for Structural Concrete.

ASTM C331: Specification for Concrete Masonry Units.

ASTM C469: Test for Static Modulus of Elasticity and Poison's Ratio of Concrete in Compression.

ASTM C495: Test Method for Compressive Strength of Lightweight Insulation Concrete.

ASTM C496: Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.

ASTM C567: Test Method for Determining Density of Lightweight Aggregate Concrete.

ASTM C995: Standard Test Method for Time of Flow of Fiber-Reinforced Concrete through Inverted Slump Cone.

ASTM C1116: Specification for Fiber-Reinforced Concrete.

ASTM C1399: Obtaining Average Residual Strength of Fiber-Reinforced Concrete.

ASTM C1550: Test Method for Flexural Toughness of Fiber-Reinforced Concrete.

ASTM C1609: Test Method for Flexural Performance of Fiber-Reinforced Concrete.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research has been partially supported by the California State University, Fresno Foundation.

References

[1] F. Furouhi, F. M. Tehrani, and A. Zand, "Two macro-economic viewpoints on light concrete application effect on national economic development," *Ravesh (Industrial Engineering) Magazine*, vol. 6, no. 35, pp. 9–11, 1996.

[2] F. M. Tehrani, *Rāhnamā-ye Jāmeʿ-e Līkā*, LECA Handbook, Tehran, Iran, 1998, http://leca.ir/wp-content/uploads/maghalat/LECA-Handbook.pdf.

[3] J. Woody Ju and F. M. Tehrani, "Macro-element modeling of steel fiber-reinforced concrete," in *ACI Spring 2008 Convention: Multi-Scale Descriptions of Concrete Performance*, ACI Committee 236, Material Science of Concrete, Los Angeles, CA, USA, 2008.

[4] F. M. Tehrani and J. Woody Ju, "Applications of moment-curvature analysis and fracture mechanics to flexural steel fiber-reinforced concrete sections," in *ACI Fall 2009 Convention: Application of Fracture Mechanics to Concrete Structures and Composites*, ACI Committee 446, Fracture Mechanics of Concrete (Joint ACI-ASCE), New Orleans, LA, USA, 2009.

[5] C. McComb and F. M. Tehrani, "Enhancement of shear transfer in composite deck with mechanical fasteners," *Engineering Structures*, vol. 88, no. 1, pp. 251–261, 2015.

[6] J. Gao, W. Sun, and K. Morino, "Mechanical properties of steel fiber-reinforced high-strength, lightweight concrete," *Cement and Concrete Composites*, vol. 19, no. 4, pp. 307–313, 1997.

[7] J. Beaudoin, *Handbook of Fiber-Reinforced Concrete: Principles, Properties, and Applications*, Noyes Publications, Park Ridge, NJ, USA, 1990.

[8] ACI Committee 213, *Guide for Structural Lightweight-Aggregate Concrete*, ACI 213 R, American Concrete Institute, Farmington Hills, MI, USA, 2014.

[9] G. Campione, N. Miraglia, and M. Papia, "Mechanical properties of steel fiber reinforced lightweight concrete with pumice stone or expanded clay aggregates," *Materials and Structures*, vol. 34, no. 4, pp. 201–210, 2001.

[10] P. Shafigh, M. Z. Jumaat, and H. Mahmud, "Oil palm shell as a lightweight aggregate for production of high strength lightweight concrete," *Construction and Building Materials*, vol. 25, no. 4, pp. 1848–1853, 2011.

[11] R. V. Belendran, F. P. Zhou, A. Nadeem, and A. Y. T. Leung, "Influence of steel fibers on strength and ductility of normal and lightweight high strength concrete," *Building and Environment*, vol. 37, no. 12, pp. 1361–1367, 2002.

[12] ACI Committee 554, "State-of-the-art report on fiber reinforced concrete," *ACI Journal Proceedings*, vol. 70, no. 11, 1973.

[13] ASTM A820/A820M-16, "Standard specification for steel fibers for fiber-reinforced concrete," *ASTM International*, 2016.

[14] M. Ramli and E. T. Dawood, "Effects of palm fiber on the mechanical properties of lightweight concrete crushed brick," *American Journal of Engineering and Applied Sciences*, vol. 3, no. 2, pp. 489–493, 2010.

[15] G. Campione, L. Cucchiara, L. La Mendola, and M. Papia, "Steel-concrete bond in lightweight fiber reinforced concrete under monotonic and cyclic actions," *Engineering Structures*, vol. 27, no. 6, pp. 881–890, 2005.

[16] O. A. Düzgün, R. Gül, and A. C. Aydin, "Effect of steel fibers on the mechanical properties of natural lightweight aggregate concrete," *Materials Letters*, vol. 59, no. 27, pp. 3357–3363, 2005.

[17] G. Campione and L. La Mendola, "Behavior of compression of lightweight fiber reinforced concrete with transverse steel reinforcement," *Cement and Concrete Composite*, vol. 26, no. 6, pp. 645–656, 2004.

[18] N. L. Libre, M. Shekarchi, M. Mahoutian, and P. Soroushian, "Mechanical properties of hybrid fiber-reinforced lightweight aggregate concrete made with natural pumice," *Construction and Building Materials*, vol. 25, no. 5, pp. 2458–2464, 2011.

[19] S. H. Ahmad, Y. Xie, and T. Yu, "Shear ductility of reinforced lightweight concrete beams of normal strength and high strength concrete," *Cement and Concrete Composites*, vol. 17, no. 2, pp. 147–159, 1995.

[20] C. Shi, Y. Wu, and M. Riefler, "Properties of fiber-reinforced lightweight concrete," *ACI Special Publication*, vol. 226, pp. 123–134, 2005.

[21] O. Kayali, M. N. Haque, and B. Zhu, "Drying shrinkage of fiber-reinforced lightweight aggregate concrete containing fly ash," *Cement and Concrete Research*, vol. 29, no. 11, pp. 1835–1840, 1999.

[22] H. Mazaheripour, S. Ghanbarpour, S. H. Mirmoradi, and I. Hosseinpour, "The effect of polypropylene fibers on the

properties of fresh and hardened lightweight self-compacting concrete," *Construction and Building Materials*, vol. 25, no. 1, pp. 351–358, 2011.

[23] D. D. Theodorakopoulos and N. Swamy, "Contribution of steel fibers to the strength characteristics of lightweight concrete slab-column connections failing in punching shear," *ACI Structural Journal*, vol. 90, no. 4, 1993.

[24] S. Kurugol, L. Tanacan, and H. Y. Ersoy, "Young's modulus of fiber-reinforced and polymer-modify lightweight concrete composites," *Construction and Building Materials*, vol. 22, no. 6, pp. 1019–1028, 2008.

[25] Y.-J. Kim, J. Hu, S.-J. Lee, and B.-H. You, "Mechanical properties of fiber reinforced lightweight concrete containing surfactant," *Advances in Civil Engineering*, vol. 2010, Article ID 549642, 8 pages, 2010.

[26] P. Balaguru and A. Foden, "Properties of fiber reinforced structural lightweight concrete," *ACI Structural Journal*, vol. 93, no. 1, pp. 62–78, 1996.

[27] B. Chen and J. Liu, "Contribution of hybrid fibers on the properties of the high-strength lightweight concrete having good workability," *Cement and Concrete Research*, vol. 35, no. 5, pp. 913–917, 2004.

[28] R. N. Swamy and A. H. Jojagha, "Workability of steel fiber reinforced lightweight aggregate concrete," *International Journal of Cement Composites and Lightweight Concrete*, vol. 4, no. 2, pp. 103–109, 1982.

[29] B. Arisoy and H.-C Wu, "Material characteristics of lightweight, high-performance concrete reinforced with PVA," *Construction and Building Materials*, vol. 22, no. 4, pp. 635–645, 2008.

[30] ASTM C1018-97, "Standard test method for flexural toughness and first-crack strength of fiber-reinforced concrete (using beam with third-point loading)," *ASTM International*, 1997.

[31] ASTM C995-01, "Standard test method for time of flow of fiber-reinforced concrete through inverted slump cone," *ASTM International*, 2001.

[32] ASTM C39/C39M-17b, "Standard test method for compressive strength of cylindrical concrete specimens," *ASTM International*, 2017.

[33] ASTM C78/C78M-16, "Standard test method for flexural strength of concrete (using simple beam with third-point loading)," *ASTM International*, 2016.

[34] ASTM C192/C192M-16a, "Standard practice for making and curing concrete test specimens in the laboratory," *ASTM International*, 2016.

[35] ASTM C496/C496M-11, "Standard test method for splitting tensile strength of cylindrical concrete specimens," *ASTM International*, 2004.

[36] ASTM C330/C330M-17a, "Standard specification for lightweight aggregates for structural concrete," *ASTM International*, 2017.

[37] ASTM C331/C331M-17, "Standard specification for lightweight aggregates for concrete masonry units," *ASTM International*, 2017.

[38] ASTM C469/C469M-14, "Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression," *ASTM International*, 2014.

[39] ASTM C495/C495M-12, "Standard test method for compressive strength of lightweight insulating concrete," *ASTM International*, 2012.

[40] ASTM C567/C567M-14, "Standard test method for determining density of structural lightweight concrete," *ASTM International*, 2014.

[41] ASTM C1116/C1116M-10a, "Standard specification for fiber-reinforced concrete," *ASTM International*, 2015.

[42] ASTM C1399/C1399M-10, "Standard test method for obtaining average residual-strength of fiber-reinforced concrete," *ASTM International, 2015*, 2015.

[43] ASTM C1550–12a, "Standard test method for flexural toughness of fiber reinforced concrete (using centrally loaded round panel)," *ASTM International*, 2012.

[44] ASTM C1609/C1609M-12, "Standard test method for flexural performance of fiber-reinforced concrete (using beam with third-point loading)," *ASTM International*, 2012.


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