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Lightweight Flexible Nonlinear Composite (LFNLC) and Elastic Composite, Reinforced Lightweight Concrete as an LFNLC

Kamyar Esmaeili*

Research and Development Department of Nogamsazegan Co., Iran.

***Corresponding Author:**

newstructure1@gmail.com

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ABSTRACT

"Lightweight Flexible Nonlinear Composite (LFNLC)" refers to a particular class of high-performance composite materials having their own structural and functional criteria like "a porous or porous-like texture" and "nonlinear behavior in bending". "Elastic Composite, Reinforced Lightweight Concrete (ECRLC)" is a cementitious LFNLC.By using this integrated structure in making the beams with "a substantially high strain capability, modulus of resilience and toughness in bending", we can provide "a significantly higher bearing capacity in considerably less weight". Meanwhile, any possibility of a brittle, compressive failure mode, especially in ultra-lightweight and low-height beams, is removed.
ECRLC, as a lightweight resilient composite, is a versatile, relatively inexpensive material. In view of the strategic importance of "lightweight and integrated construction" in improving earthquake resistance, ECRLC can especially be useful in "seismic areas". Allowing for the behavior and resilience of this flexible system and its formability, it can also be utilized in making "ultra-lightweight and insulating, Non-brittle reinforced sandwich panels", lightweight, safe guards, shock-resistant structures, some infrastructures, and blast-proof pieces with appropriate behavior, resilience and toughness.
Lightness is important in saving energy and reducing the total cost of building construction too. In this paper, the main structural and functional particulars of LFNLC, some applications, and a Reproducible, simple instance of ECRLC have been briefly presented.

Keywords: Strengthening, Lightweight Flexible Nonlinear Composite (LFNLC), Elastic Composite Reinforced Lightweight Concrete (ECRLC), Explosion, Absorber, Railroad, Concrete

Introduction

What is termed "Lightweight Flexible Nonlinear Composite (LFNLC)" or "Lightweight Resilient Nonlinear Composite (LRNLC) refers to a particular class of composite structures. The main functional criterion of LFNLC is nonlinear behavior in bending, and the structural criteria have been presented later in this paper.
They are specifically made by "suitably creating disseminated suitable hollow pores and/or by distributing (dispersing) suitable lightweight aggregates (like Expanded Polystyrene Beads) throughout a methodically reinforced conjoined (well-integrated) matrix" *so that* the overall behavior of the system in bending is principally *nonlinear*. By applying this applied method to make such a lightweight nonlinear structure, *"considerably increasing the modulus of resilience, the bearing capacity and the toughness in bending"* concomitant with *"the significant decrease of the weight"* and *"the removal of the possibility of failing in a brittle, compressive mode"* have been *concurrently* feasible. Through making these integratedly

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(congruently) operating systems, the stated paradoxical virtues are fulfilled in one operating unit *altogether*.

In view of the area under the stress-strain curve (especially till the point of elastic limit) and the curve shape, LFNLC can be counted as a flexible nonlinear structure with *high capability of strain*, modulus of elasticity and toughness in bending.

In general, the density of LFNLC is less than 1920 kg/m^3.

The LFNLC with the density of about 800 kg/m^3 or less is called *"Super Lightweight Flexible Nonlinear Composite (S-LFNLC)"*. Here, unlike ordinary reinforced lightweight concretes, more emphasis is placed on the flexible ultra-lightweight composites with a density of about 800 kg/m^3 or less. *Upon the case, S-LFNLC can even have "more performance and merits" in practice.* (In addition, owing to the considerably low density, it could be counted as a *thermal insulation*.)

Considering the texture of the conjoined matrix of any LFNLC, the terms like "Porous-like Flexible (Resilient) Composite" and "Porous-like Nonlinear Composite" could also be taken into consideration to point out such type of lightweight flexible structure. However, these terms seem to be arguable, and the meaning of the word "porous-like" in this case should be cleared.

Of note, the term "Resilient Composite Systems (RCS)" has formerly been used, in the related literature [1], to refer to the class of composite structures here named "Lightweight Flexible Nonlinear Composite (LFNLC)". Considering some important differences among the particular composite materials classified as "Lightweight Flexible Nonlinear Composite (LFNLC)" and other resilient composites, like those called "Engineered Cementitious Composite (ECC)" [2] [3] [4], here, the term "Lightweight Flexible Nonlinear Composite (LFNLC)" has been used instead of the terms like "Resilient Composite Systems (RCS)" [1] and "Lightweight Resilient Composite (LRC)" [5]. [The term "Engineered Cementitious Composite (ECC)" is usually employed to refer to a particular class of High-Performance Fiber-reinforced Cementitious Composites (HPFRCC), also named "Strain Hardening Cement-based Composites (SHCC)". It has also been popularly called "Bendable Concrete (Flexible Concrete, Foldable Concrete)" [2, 3, 4]].

Anyhow, LFNLC is a high-performance flexible composite structure too, which could have *more flexibility* and *less density* compared with the ordinary ECC.

Notwithstanding some similarities, the essential components and structural & functional criteria and specifications of LFNLC are not the same as those of some other so-called flexible composites like ECC. For instance, the LFNLC density could be considerably less than the ordinarily ECC density, and the suitable pores and/or lightweight aggregates, disseminated throughout a methodically reinforced conjoined matrix, play a fundamental role in the properties and special function of LFNLC.

However, it is also feasible to merge these technologies into one integrative system. For instance, by properly reinforcing the structure called ECC with an appropriate lattice (like a suitable mesh) along with properly creating disseminated suitable hollow pores and/or distributing suitable lightweight aggregates throughout the structure, we can have a kind of LFNLC. *Flexibility of this lighter structure, with high modulus of resilience and toughness in bending, will be more than that of the mentioned ECC (with a higher density). This way, the weight can be reduced and the performance can be improved upon the case.*

In general, in LFNLC, the virtues as *lightness* and significantly high *capability of strain (strainability)*, resilience and toughness "in bending" are particularly prominent.

Further clarification of some discussions formerly presented, by the author, in the related literature and the necessary correction, modification and improvement of some topics regarding the subject necessitated this summarizing paper. This concise but comprehensive paper substantially includes the essence of the former related literature in an upgraded form.

Structural and Functional Criteria of Lfnlc

The structural and functional particulars as stated below are necessary to count a composite structure as a "Lightweight Flexible Nonlinear Composite (LFNLC)".

Structural Criteria and Essential Components

In general, any LFNLC includes the components as below. The composition of these *essential elements* within the system is *so that* the interactions among the constituents ultimately bring about the main functional characteristic of such kind of lightweight composite, as nonlinear behavior in bending, in practice.

A) Skeletal Mesh: Considering the Ferrocement technology [6, 7, 8, 9], steel wire meshes are the instances of such reinforcement. If expedient, some suitable nonmetal meshes, like those made of Fiber Reinforced Polymer (FRP), can be utilized too. In any case, "the modulus of elasticity and elastic strain limit (ε_y) in tension of the lattice" must be higher than "those of the lightweight, fiber-reinforced matrix", and the meshes with appropriate dimensions mush be used.

B) Fibers: Various types of fibers with acceptable elasticity can be used in LFNLC. For instance, polymer fibers, like polypropylene fibers (which is a widely-use material, also having good resilience to impact), are among such fibers [10, 11, 12].

In any case, similar to some of other fiber-reinforced materials, "the modulus of elasticity and the elastic strain limit in tension of the fibers" must be more than "those of the binding substance of the system when

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containing the same lightweight aggregates and/or the hollow pores (but not containing the fibers)".

Likewise, the presence of the fibers with a length more than the longest length of the pores or the used lightweight aggregates (when they are at their maximum stretch in the structure) is another requirement for an effective fiber reinforcement.

C) *Conjoined* (well-integrated, congruent) matrix *also having the disseminated suitable pores and/or the disseminated suitable lightweight aggregates*: [Here, the term of "lightweight aggregate" has a broad meaning, including various types of lightweight polymeric and/or non-polymeric beads, particles, etc.]

When lightweight aggregates are used, "the modulus of elasticity in compression of the aggregate" is required to be less than "that of the lightweight, fibrous matrix (also containing the lightweight aggregates and fibers) employed in the system".

In view if *the presence of the pores and/or the lightweight aggregates throughout the matrix to reach a so-called porous or porous-like texture*, this *lightweight* matrix cannot be counted as a homogenous substance; however, it must be necessarily *well-integrated*, and can have *a good bond with the reinforcement*.

In general, using as much as smaller pores and/or smaller lightweight aggregates and employing the lightweight aggregates with higher modulus of elasticity in compression (but still lower than that of the lightweight, fibrous matrix of the structure) as well as utilizing more appropriate and resilient fibers and lattice can give rise to the better behavior, modulus of resilience and endurance limit in compression and bending [This point is especially important in making some infrastructures that are under continual dynamic loads for a long term].

In general, the matrix of LFNLC can mainly include polymeric materials and/or non-polymeric materials (like C-S-H crystals) as the binding substance. This way, we can have "Polymer-based or Polymeric Lightweight Flexible Nonlinear Composite (Po-LFNLC)", "Cement-based or Cementitious Lightweight Flexible Nonlinear Composite (Ce-LFNLC)" (which is also termed Elastic Composite, Reinforced Lightweight Concrete, ECRLC), and other kinds of Non-polymer-based LFNLC.

♦ An instance of lightweight, fiber-reinforced conjoined matrix used in ECRLC:

A special fiber lightweight concrete, also containing the beads of expanded polystyrene (EPS), as an ultra-lightweight aggregate with very little water absorption, is a good *instance* of the substances that can be used as the lightweight fibrous matrix of ECRLC [Employing EPS beads to lower the concrete density [13, 14, 15, 16] is a known method also pointed out in the classic references regarding ordinary lightweight and insulation concrete [17]]. This special pozzolanic fiber lightweight concrete has some virtues as follows: lightness; high strain capability (within the elastic limit) and high ductility (beyond the elastic limit) in compression, overall bringing about *an appropriate ratio of toughness to density (specific toughness) in compression*; a non-brittle failure mode in compression; a good bond with reinforcement; acceptable durability, and good workability (also including formability).

The stress-strain diagram of the fibrous EPS concrete, stated above, in compression has been shown in figure 1.

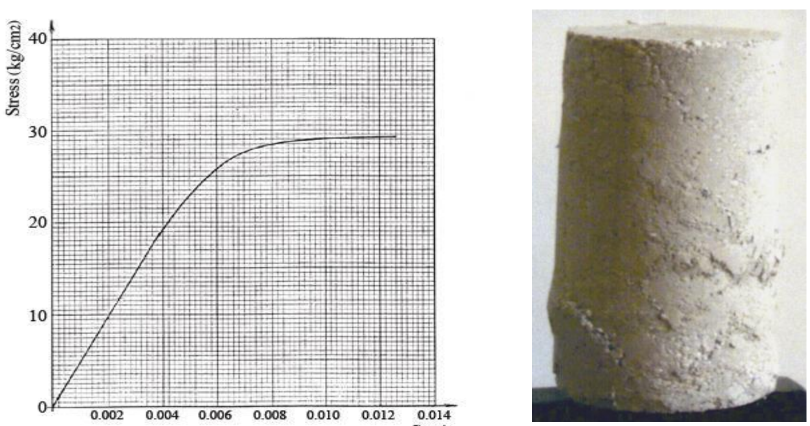

Figure 1. The stress-strain curve of a special fiber-reinforced EPS concrete, also containing the EPS beads, in compression

- Oven-dry density = 600 kg/m^3, f'_c = 29.5 kg/cm^2 in 28 days; Ratio of *Silica Fume* to Portland cement (Type II) = 8.5%, Water-to-Binder Ratio (W / C+S) = 0.425 (with using Lignosulfonate as a low-price plasticizer and retardant); Monofilament Polypropylene Fiber (Denier 3) = 1.1% of volume of the concrete. [Here, n*o*

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gravel, sand, and/or any other inactive fines have been employed; *"only binding substances as cementitious materials"* have been used in the matrix (having a so-called porous-like texture)].

- In this case, contrary to ordinary concrete, the ultimate axial strain at the point of the final, complete failure in compression (ε_{cu}), in its current sense as a certain and exact value, cannot be determined. (ε_{cu} ↑) [Likewise, the Stress Block Coefficients (α and β) are high].

Functional Criteria

As it was stated formerly, in LFNLC, the amount and the use manner of the main components in the organized system are *so that* the reciprocal interactions among the congruent constituents overall bring about *the nonlinear behavior of the structure in bending*, as the main functional characteristic of such congruently operating units.

In LFNLC, the main strategy to raise the modulus of resilience in bending is *increasing the strain capability (strainability) of the system in bending within the elastic limit*. And, the main tactic to realize this strategy is *creating the suitable hollow pores and/or using the suitable lightweight aggregates, disseminated throughout the methodically reinforced conjoined matrix*, in order to provide the essential possibility for occurring of the internal deformations in the matrix during bending *in a particular manner*. (This particular manner of occurring of the internal deformations can lead to the more appropriate distribution of the stresses and the strains throughout the system and the more strain capability of the beam in bending).

Obviously, only creating the hollow pores and/or using the lightweight aggregates in the matrix, by itself, not only could not lead to the stated goals but also would cause the fragility due to weakening of the matrix. Hence, in addition to the necessity of having *a lightweight and conjoined (well-integrated, congruent) matrix with high strain capability*, it is required to systematically support and strengthen the matrix by applying the expedient reinforcement in a reticular arrangement.

Along with providing the internal consistency of the matrix, it is supported by methodically employing the reinforcement in at least two forms: A) lattice (mesh), B) fibers. Systematically applying these supports inside the lightweight, conjoined matrix brings about the better distribution of the tensile stresses and strains throughout the system. This distribution pattern of the stresses and the strains throughout the structure increases the endurance and modulus of resilience in tension and bending and enhances the flexibility by withstanding the strains. As it was remarked, the presence of the mentioned hollow pores and/or lightweight aggregates, well disseminated throughout the reinforced conjoined matrix, provides *the necessary possibility for occurring of the internal deformations in the matrix during the bending course "in a particular manner"*. This particular manner of the internal deformations occurrence leads to the less accumulation of the internal stresses in any certain points of the matrix during bending, the better absorption and control of the stresses, and the more strain capability of the beam especially within the elastic limit.

Through the bending course, the internal deformations, in the matrix, occur in the two main different forms, involving: I) The comparative increase of the thickness (height) of the in-compression layers (especially in the upper parts of the beam) and the conversion of some internal compressive stresses to the internal tensile stresses (on the axis perpendicular to the mentioned internal compressive tensions) in the in-compression layers; II) The comparative decrease of the thickness (height) of the in-tension layers (particularly in the lower parts of the beam) and the conversion of some internal tensile stresses to the internal compressive stresses (on the axis perpendicular to the mentioned internal tensile stresses) in the in-tension layers.

In the under-bending sections of LFNLC, the deformations occurring in "the adjoined layers perpendicular to the applied load direction" during the bending course are *so that* "the initially plane sections that are perpendicular to the beam axis" *principally* shift from "the plane (straight) status" to "the curve status" (⤶ ⤷). Indeed, in LFNLC, the mentioned internal deformations in the beam during the bending course results in the tendency of the so-called neutral axis of the beam to move downward. (This tendency to move downward is opposite to the tendency of the neutral axis of ordinary reinforced concrete beams to move upward during the bending course. Upon a basic *assumption* of flexural theory, "the sections perpendicular to the axis of bending that are plane before bending remain plane after bending" [18].) In these particular lightweight composite structures, contrary to the fundamental assumption of flexural theory and the relating kinematic and geometrical equations (discussed in solid mechanics and strength of materials), the strain changes in the beam height during the bending course are *principally nonlinear*. (In other words and like any other so-called flexible nonlinear materials, "the height of the beams made of this flexible composite" is reduced principally more than "that of the beams made of the so-called linear materials"). Thus, the said fundamental assumption and the respective geometry-trigonometric ratios and equations do not apply to the beams made of LFNLC; those relations and equations lose their meaning and applicability in this case. Through occurring of the remarked internal deformations in the methodically supported lightweight, conjoined matrix of the structure during the bending course, the stresses are more distributed and absorbed, and "the rate of the accumulation and rise of the internal stresses in any

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certain points of the matrix, during the bending course," lessens. All in all, by better withstanding the strains during the bending, the more strain capability of the beam made of LFNLC in flexure is provided. Obviously, ECRLC, as a particular class of complex materials, naturally displays anisotropic properties.

Elastic Composite, Reinforced Lightweight Concrete (Ecrlc)" as a Kind of Lightweight Flexible Nonlinear Composite (Lfnlc)

As it was stated, "Elastic Composite, Reinforced Lightweight Concrete (ECRLC)" is a kind of "Lightweight Flexible Nonlinear Composite (LFNLC)" whose matrix is mainly cementitious. [Two types of cementitious materials are hydraulic cement and supplementary cementitious materials (SCMs). The cementitious materials mainly include Calcium-Silicate-Hydrate (C-S-H) crystals as the binding substance. Silica fume (micro-silica, silica dust, nano-silica), as a pozzolanic material, is an instance of SCMs, which can affect various aspects of the concrete [19, 20].

ECRLC can be considered a Cementitious Nonlinear Composite. In view of the particalar behavior of this cement-based lightweight *nonlinear* composite in bending, "strain capability (especially within the elastic limit), energy absorption capacity and bearing capacity of the beams made of ECRLC" are overall more than "those of similar ordinary reinforced concrete beams".

The presence of the hollow pores and/or the lightweight aggregates brings about the low density of the structure in total. As a kind of LFNLC, the density of ECRLC is less than 1920 kg/m^3. Anyhow, by expediently employing ECRLC, we can easily reach the very lightweight structures with the densities of *about or less than 800* kg/m^3, which could also be considered thermal insulation. [In general, any concrete with an oven-dry density of less than 800 kg/m^3 can be classified as thermal insulation concrete (insulating, insulator, or insulative concrete) [18].

By utilizing ECRLC, some substantial problems in using lightweight concrete, like the high possibility of a brittle, compressive failure mode in the beams made of ordinary reinforced lightweight concrete (especially in those with low height and/or made of very low density concrete as insulation concrete), can be solved. *Then we can also reach the ultra-lightweight and low-height beams with a significantly high bearing capacity.*

In consideration of the issues stated about LFNLC, the results of flexural tests done on the slabs made of ECRLC, *with and "without" supplementary tensile steel bars*,in a method similar to ASTM E 72 are noticeable [1, 21, 22].

In the analysis of the slabs made of ECRLC (with and *without* the supplementary rebar) to calculate the nominal strength in bending via the method called "Ultimate Strength" [18, 23], the *nominal* strength (M_n) has been *much less* than the *actual* (true) strength in practice. (This considerable difference has been more evident in the case of the tested slab not having any supplementary (accessory) tensile steel bar.) [Of note, the ultimate strength method and many equations commonly used for the analysis of the structural behavior of the beams made of ordinary reinforced concrete in bending are based on the said fundamental assumption of flexural theory [18].

Likewise, the actual amounts of "the cracking moment (M_{cr})", "the modulus of resilience ($u = ½\, \sigma_y \cdot \varepsilon_y$)", and most of all *"the elastic strain limit (ε_y)"* in bending in practice have been *substantially higher* than the corresponding nominal values obtained from the routine ratios and equations commonly used for analyzing ordinary reinforced concrete slabs.

Even when the concrete compressive strength in the respective equations (based on the said fundamental assumption of flexural theory) mathematically tends to infinite (∞) and the stress block height is supposed to be equal to zero, the actual strength, in the flexural test, in practice has still been higher than the M_n.

Indeed, in view of the actual behavior of the slabs made of ECRLC through the bending course, despite much increase of the tensile forces in the slab in bending than what is called "compressive block strength" *obtained from the routine relations & equations based on the said fundamental assumption of flexure* [18, 23], the strain of the slab still continues until reaching the actual maximum capacity of strain.

In this way, *making more use of the strength capacity of the tensile reinforcement* has been possible. It is due to the deformation occurrence manner of the beams through the bending course and the more strain capability of such beams in bending.

Despite the large amount of the tensile reinforcement employed in the slabs, they have not failed in a flexural compression mode. Especially in the case of the slabs having the supplementary tensile steel bars, the tensile reinforcement have been *considerably more* than the balanced steel ratio; nonetheless, the failure of the beam has not occurred in a flexural compression mode. [What is termed balanced steel ratio (ρb), used to prevent compression failure mode, is routinely calculated upon the usual ratios and equations of ordinary reinforced concrete beams ($\varepsilon_{cu} = 0.003$). These ratios and equations are based on the mentioned

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fundamental assumption of flexural theory too [18, 23]. In any case and as a rule, the beams made of LFNLC do not fail in bending in a flexural compression mode.

"A Reproducible, simple instance of the lightweight flexible slab made of ECRLC", additionally reinforced with supplementary tensile steel bars as accessory supportive reinforcement, has been shown in *figure 2* in detail. [Here, "*the Mix Design" of the special pozzolanic fiber-reinforced lightweight concrete used as the lightweight, fiberous conjoined matrix of the said composite structure* and all details required for any replication of the tests have been presented too].

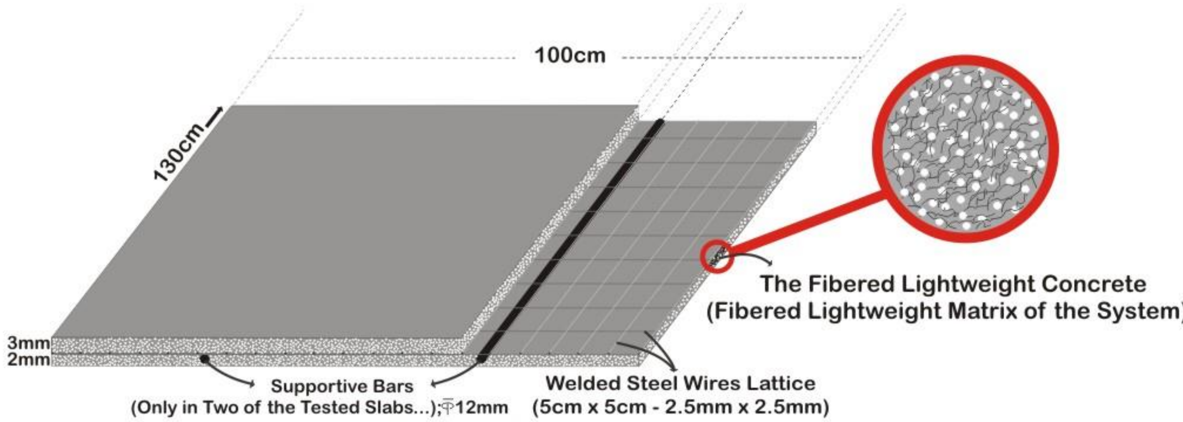

Figure 2. A "Reproducible", simple instance of the lightweight flexible slab made of ECRLC (as a kind of LFNLC), Additionally reinforced with supplementary tensile steel bars

● Dimensions of the slab: L ≈ 120 cm, h ≈ 5 cm, b ≈ 100 cm

● Particulars of the welded steel wire mesh made of *cold-drawn steel wires*:

5 cm × 5 cm – 2.5 mm × 2.5 mm

$f_{y1\ (Mesh)} \approx 4672\ kg/cm^2$, $A_{s1\ (Mesh)} \approx 0.98\ cm^2$, $d_{1\ (Mesh)} \approx 3$ cm, $E_s \approx 2\times10^6\ kg/cm^2$

[The longitudinal wires of the lattice (with the length of 120 cm) are placed on the transverse wires of the lattice (with the length of 100 cm).]

● Particulars of the supplementary tensile steel bars (as the accompanying element)

$f_{y2\ (Bar)} \approx 4400\ kg/cm^2$, $A_{s2\ (Bar)} \approx 2.26\ cm^2$, $d_{2\ (Bar)} \approx 3.9$ cm, $E_s \approx 2\times10^6\ kg/cm^2$

● Particulars of the special pozzolanic fiber-reinforced lightweight concrete as the lightweight, fibrous conjoined matrix of the structure, containing expanded polystyrene beads (as the lightweight aggregates distributed throughout the matrix):

$f'_c \approx 64\ kg/cm^2$, $f_r \approx 34.5\ kg/cm^2$, $f_{ct\ (Brazilian\ Method)} \approx 14.5\ kg/cm^2$, $E_c \approx 4\times10^4\ kg/cm^2$,

Oven-dry density ≈: 835 kg/m^3, Drying shrinkage after 90 days (measured by testing a sample of the fiber-reinforced EPS matrix outside the slab): less than 0.015.

- The mix design of the said special pozzolanic fiber-reinforced EPS concrete as the lightweight and strainable conjoined matrix of the system in this case: Portland cement (Type II) + Silica Fume (8.5% of the Total Cementitious Materials) ≈ 675 kg/m^3; Water-to-Binder (the Total Cementitious Materials) Ratio (W / C+S) = 0.425 (with using Lignosulfonate as a low-price plasticizer and retardant); monofilament polypropylene fibers (denier 3) ≈ 12.6 kg/m^3 (with the two different lengths: two portions of the fibers of 12 mm length and one portion of the fibers of 6 mm length); expanded polystyrene (EPS) beads ($D_{50} \approx 3.2$ mm) up to 1 m^3. [If the finer beads, e.g. with $D_{50} \approx 1$ mm, are used, the f'_c will be increased.] [Naturally, the high difference between the apparent density of the EPS granules and the true density of them must be considered in the mix design calculation].

- *No gravel, sand, and/or any other inactive fines* have been employed in the conjoined matrix of the system; *"only binding substances as cementitious materials"* have been utilized in the matrix (having a so-called porous-like texture). [If any inactive fine is used in producing such composite structures, it must be very small and well conjoined to the cementitious materials of the matrix; otherwise, the incongruency will dramatically cause serious disturbances in the behavior of the system and bring on the problems such as brittleness and considerably falling of the modulus of resilience and the toughness in bending. (Until now, it has been preferred that no inactive substance, like sand or rock soil, as the fine be employed in the matrix)].

- Curing of the fiber-reinforced lightweight cementitious matrix of the structure has been performed via the so-called Membranous Method (for 30 days).

- The welded points on such steel wire meshes, as the possible weak points of the meshes in high tensions, should be given special attention in the manufacture of these meshes. In our experiences, the final failure of

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the slabs in very high bending loads occurred owing to the rupture of the wires from such weak points.

- Of note, the presence of any supplementary element, like the tensile steel bars shown above, is *Not a necessary condition* to count a structure as LFNLC or ECRLC. Here, considering the tests performed on the slabs, which some of them had been additionally reinforced with the supplementary bars, the used supportive bars have been shown. *[In practice, such supportive ("protective") bars, under the mesh, could also be employed in some low-height slabs "to prevent any final, complete rupture and separation of the slab" under severe tension at unpredicted very high loads]*.

- In any repeat of such experiences, it is recommended the tests are performed on the slabs having and those *Not* having the supplementary reinforcement, like bending steel bars, under similar conditions.

Applications

Allowing for the virtues of LFNLC and the mentioned applied method to make this lightweight and flexible composite, there are several applications in various fields.

Some Applications in Building Industry

LFNLC can be used in constructing the elements subject to bending, shock, and vibration. This versatile material can be utilized to make curved and flat roofs, floors & decks, walls & partitions, multi-floor parking garages, dome-shaped buildings, etc.

In general, ordinary reinforced ultra-lightweight concretes can be dramatically *brittle* [12]; they do not have appropriate behavior, resilience and toughness in bending, shock and impact. This notable problem is more evident in the elements having low thickness (like slabs and thin walls) and/or in those made of very lightweight concrete like insulation concrete with a density of less than 800 kg/m^3. By employing ECRLC, this substantial problem can be removed. *This special merit of ECRLC has a crucial importance especially in seismic areas.*

Lightness has a decisive role in thermal insulation and *saving energy* too [17, 24].

In addition to *the speed and ease of constructing*, lightness is a significant *economic advantage*, especially in constructing tall buildings like towers. By employing LFNLC, the weight can be considerably reduced. (For instance, by utilizing the ultra-lightweight and flexible insulation materials instead of some conventional materials, the total weight has been reduced to about one-sixth in some cases).

It can also be used for the *rehabilitation* and strengthening of some old structures. In general, the virtues as follows have high importance in *architecture* too: lightness, durability, resilience and flexibility, workability and formability (like *the capability of easily creating curved surfaces and complex shapes and implementing various architectural designs*).

Likewise, allowing for some properties of the high-performance matrix used in LFNLC and the possibility of applying any expedient supplementary elements and materials, the lightweight fibrous matrix of LFNLC can have a variety of applications. *For instance,* some virtues of a special *pozzolanic* fiber-reinforced ultra-lightweight concrete that has been used as the matrix of ECRLC were mentioned before.

Here, it should be highlighted that, *if needed and according to the case, any expedient supplementary elements and materials can be employed concomitant with LFNLC.* Accompanying reinforcement, connective strips, high strength mortars, various foams, and the like could be among such supplementary elements and materials. The supplementary elements and materials, upon the case, can improve the integrity, strength, and duration of the matrix and enhance the overall behavior and resistance of the structure particularly in bending and to the severe impact and continual dynamic loads. However, the supplementary elements and materials are not necessary to count a system as an LFLNC.

Using LFNLC to improve the earthquake resistance of buildings

In general, "lightweight and integrated (congruent) construction" can be considered a pivotal and practical tactic to increase the resistance of buildings to earthquake and lateral forces, on the large scale. ECRLC, as a kind of LFNLC, can be utilized to broadly implement this key tactic to withstand seismic loads [1, 22, 25].

In general, the items as follows are also important in the resistance and the safety of constructions against earthquake: lightness; integrity (not employing the separated materials and elements with discordant behavior); high modulus of resilience and the high capacities of energy absorption and reserving; appropriate behavior against shock; having a safe failure mode; etc. Using lightweight and congruent materials, within the framework of an integrated system, can have a substantial impact on improving the resistance to earthquake and lateral forces.

Of note, applying the stated practical method to make LFNLC, particularly as ECRLC, as well as using ECRLC in construction has been accomplished for the first time, in the first half of 2000s, in Iran [1, 21, 22, 25]. It was done especially in view of the high risk of earthquake in Iran as one of the most seismically active countries.

[In general the systematic and widespread promotion and implementation of *"lightweight and integrated construction"*, as the key tactic stated above, can be considered a practical policy to raise the earthquake resistance of buildings, on the large scale. Likewise, the continual and extensive presentation of the suitable materials and construction systems to fulfill "Lightness

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and Integrity", along with meeting other requirements in buildings, can be highly influential in the promotion and realization of the said tactic in various ways].

Employing ECRLC, as a kind of LFNLC, in making ultra-lightweight and insulation, non-brittle reinforced sandwich panels

The lightweight panels made of ordinary reinforced ultra-lightweight concrete, like insulation concrete, are usually *brittle*. The behavior, resilience and toughness of them in bending, shock and impact are not appropriate. By handily employing LFNLC, we can get access to very lightweight panels with desired virtues.

A kind of LFNLC that is termed ECRLC, with acceptable durability, can be utilized in easily making ultra-lightweight and insulation, *non-brittle* reinforced sandwich panels (relatively similar to the so-called "3D-panels"), also having appropriate behavior in shock and impact. Using ECRLC in making such *"non-brittle ultra-lightweight panels"*, which are employed as non-load-bearing interior and exterior walls, is *"a very simple and practical application of LFNLC"*.

These panels can be *cast-in-place* or precast upon the case.. For instance, the mix design of a special pozzolanic fiber-reinforced ultra-lightweight concrete that has already been used in making the said ultra-lightweight, *Non-brittle* panels is as follows: Portland Cement + *Silica Fume* (7% of the total cementitious materials) = 550 kg/m^3 [The type of portland cement is selected upon the related factors. Many times, portland cement type II (modified) could be a good choice.] [If expedient and upon the case, it is also possible to replace silica fume with some other *suitable* pozzolanic materials together with appropriately modifying the amounts of the portland cement, EPS beads, additives, and water-to-binder ratio in the mix design [20, 22]; Water-to-Binder Ratio (W / C+S) = 0.4, Lignosulfonate Powder (as a low-price plasticizer and retardant) = 1.1 kg/m^3, Polypropylene Fibers (Denier 3, Length 12 mm) = 1.265 kg/m^3 [These fibers could be well blown and then blended with a little silica fume, before adding to the mix, in order to better separation and distribution of the fibers.]; Expanded Polystyrene (EPS) Beads ($D_{50} \leq 3.2$ mm) up to 1 m^3. [In general, for such applications, the EPS beads with as fewer true densities as possible are economically preferred. Likewise, using the beads with as smaller sizes as possible (like the EPS beads called fine or especially super fine) can have a positive impact on some mechanical properties of the EPS concrete.

However, in each situation, the price of the beads, as an important economic factor, should be regarded too]. [Here, *no gravel, sand, and/or any other inactive fine* have been employed; *"only binding substances as cementitious materials"* have been used in the matrix (having a so-called porous-like texture).] [All of the ingredients ought to be *well mixed*, e.g. for *at least 15 minutes*. The obtained paste can easily be applied on the surface. The slump of the relatively sticky fibered cementitious paste, as a formable and easily-molded material, is about zero. (The oven-dry density of this instance of very lightweight and insulation fiber-reinforced EPS concrete is about 660 kg/m^3, and its density in the usual normal condition could be about 730 kg/m^3)].

In the mentioned ultra-lightweight, non-brittle panels, the steel wire meshes and the fire retardant polystyrene sheet (employed as the insulation and also mold between the two layers of the steel wire meshes) could have various dimensions according to the case. For example, it could be "8 cm × 8 cm - 3 mm × 3 mm" for the steel wire meshes (as the welded meshes made of the cold-drawn steel wires), and 5 cm diameter for the polystyrene sheet. [Considering the mentioned application, as the non-compression-load-bearing walls, here, the usual distance between the polystyrene sheet and the steel wire meshes used in the panel is not *necessary*. (The stated distance is required in the ordinary compression-load-bearing 3D wire panels.) Likewise, the truss wires, connecting the two wire meshes placed on the two sides of the panel, is not *necessary* in the non-compression-load-bearing panels.]

The diameter of the utilized fiber-reinforced EPS concrete on each side of the sandwich panel could, for instance, be about 2-3 cm. This way, in the usual normal condition, the total weight of the finished non-bearing wall (made of the mentioned insulation, *non-brittle* reinforced sandwich panels) with the expedient thin coverings (as plaster) could, in practice, be about 50-65 kg/m^2].

Allowing for a construction system known as 3D panel technology (SRC Panel System by employing the tri-dimensional wire panels and sand-cement mortar), the implementation method of the said very lightweight non-brittle sandwich panels can easily be spread. [To facilitate the process, if expedient, it is also possible to broadly provide a "Dry Mix", with or *without* portland cement, in *standard* packages.] (More discussions on this topic have been presented in the related literature [22, 25, 26].

In general, the items as follows are also considered in selecting any material and construction method: speed and ease of transportation and installation and low waste of materials; heat insulation; moisture insulation; being an obstacle to sound; resistance to fire; durability; the rates and amounts of any shrinkage and creep; any capability of self-healing; workability also including formability and the capabilities (facilities) of cutting, sawing, abrading, repairing, nailing, holding screws, installing installations, and applying the coverings and paints; the amount of covers and coatings, like stucco or plaster, that can be adequate for finishing the surface; usable in-door space; etc. (Some simple instances of easily utilizing ECRLC and the mentioned

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special fiber EPS concrete in construction have been shown in figure 3).

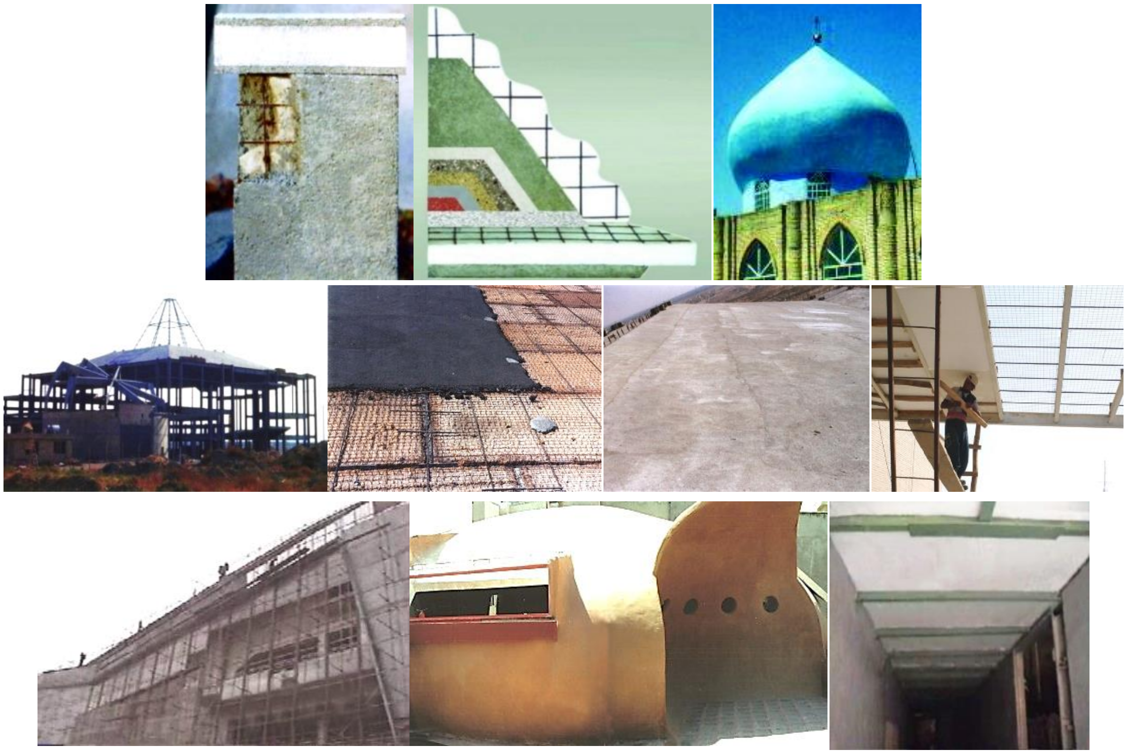

Figure 3. Some simple instances of easily using ECRLC and the mentioned special fiber EPS concrete in construction

Some Other Feasible Applications

This lightweight flexible composite can also be used in making the shields and structures absorbing shock and vibration, accompanied by employing any expedient supplementary elements and materials according to any particular case. Some instances of such shields & absorbers are *lightweight and safe roadside barriers and guards* and the *protective shields* against projectiles (such as shrapnels) and blasts.

Likewise, it can be used in constructing *bridges*, some *retaining structures*, and some *infrastructures* like the *slab tracks* and pieces under the rails and roads.

In addition, LFNLC and the respective formable matrix, like the lightweight fiber matrix of ECRLC, could be employed in constructing *floating and marine structures* and *various objects* such as pips and ducts, lumbers, cabinets, counters, lightweight facade pieces, evaporation-barrier floating pieces, and so forth.

[Of note, a noteworthy type of "Floatable, Lightweight Cement Composite (FLCC)" has been presented by some researches [27]. Anyhow, in consideration of the materials used in that reinforced ultra-lightweight concrete, like the matrix constituents and the inelastic glass microspheres as the lightweight aggregates, its overall behavior in bending cannot be principally nonlinear; it cannot be considered an LFNLC].

Discussion

In this section, the key points and some further work and studies proposed for future have been presented.

Key Points

This work implies an innovative method *"to convert a rigid solid into a flexible material with less density" or "to raise the elasticity of a flexible material plus reducing the density"*. The method involves "creating what is called a porous or porous-like texture" along with "appropriately reinforcing the material" as well as "providing the necessary integrity". Creating the porous or porous-like texture is done by "generating disseminated suitable hollow pores" and/or "distributing suitable lightweight aggregates" throughout the reinforced matrix. In this way, we can "raise *the capability of strain*, the modulus of elasticity and the toughness in bending" *together with "reducing the density"* as well as "the removal of the possibility of failing in a brittle, compressive mode".

The high-performance materials classified as "Lightweight Flexible Nonlinear Composite (LFNLC)", having a significantly high performance/weight ratio, can be made via the practical method mentioned above. LFNLC is a lightweight methodically reinforced, flexible nonlinear material with *an especially high specific*

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modulus of resilience and toughness in bending. (The ratios of the *modulus of elasticity and the toughness, in bending, to density* are particularly high).
For instance, by applying the mentioned method, it is feasible to make flexible (resilient) *ultra-lightweight* concrete with *more flexibility and performance* even compared with the ordinary engineered cementitious composite (ECC).
ECRLC, as a cement-based LFNLC, is a versatile, novel material. Likewise, compared with some other high-performance composites and materials, ECRLC is relatively low-cost. It can especially be used to broadly implement *"lightweight and integrated construction" as a practical, pivotal tactic to improve the earthquake resistance of buildings, on the large scale*, too.

Further Work and Studies Proposed for Future

Considering the development history of "Cementitious Composite Materials (CCM)" [28], work on FLNLC structures, especially those having a very low density, can be advanced and eventually go *beyond the cement-based composites*. Anyway, as much as developing these advanced materials and their applications in various fields demand further work in a variety of fields within an interdisciplinary approach.
To this purpose, some related technologies, such as ferrocements [6, 7, 8, 9, 25], ECC [2, 3, 4, 29, 30, 31], and the like, can be taken into consideration. It is also possible to merge some related technologies into one integrative system.

- Likewise, the effects of using the substances as follows on the qualities of LFNLC can be studied: various lightweight aggregates like High Impact Polystyrene (HIPS) [32, 33] and some other kinds of lightweight elastomeric aggregates; various amounts, kinds, forms and sizes of fibers (like nanofibers, microfibers, and larger fibers); some hydrophilic fibers and substances; varied kinds and forms of meshes such as those made of High-strength Steel (HSS) and those made of non-steel materials (like Fiber Reinforced Polymer (FRP) such as Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), etcetera); any other materials that could enhance the integrity, elasticity and resilience of the system.

Another idea is increasing the amount of micropores throughout the matrix via calculatingly raising the water-to-binder ratio in the matrix mix design. It should be done together with modifying the rheological properties of the paste (for instance, by utilizing suitable pozzolanic materials, latex-based additives, etcetera) as well as employing the expedient blended fibers (also including the fibers with very small sizes) and paying attention to the water absorption properties of the final product.

- In view of the binder amount and the reinforcement, like fibers, used in ECRLC, and considering the capability of self-healing in the ECC structures [31], it is proposed that the self-healing capability of the ECRLC structures be studied too.

- One of the priorities to promote broadly using LFNLC in making beams is presenting the relevant models & equations for a true analysis of the behavior of the LFNLC structures in bending. Up to now, in the routine building construction, we have usually applied "the same equations commonly used for the analysis of ordinary reinforced lightweight concrete beams" for the analysis of ECRLC structures too. (Anyhow, considering the particular behavior of LFNLC structures in bending, there is no need to the calculation of the balanced reinforcement ratio in the ECRLC beams.) In this way, in practice, the actual (true) bearing capacity and toughness of the elements made of ECRLC in flexion have been very higher than the nominal values obtained from the common equations. The equations routinely employed for the analysis of ordinary reinforced concrete beams are upon on the stated fundamental assumption of flexural theory, which is not the case with the LFNLC beams.

When an LFNLC like ECRLC is used in making non-load-bearing elements (like "lightweight and insulation, non-brittle reinforced sandwich panels"), the relevant requirements and standards must be regarded; but there is no need to any specific equations for a true analysis of such nonlinear structures in bending. *As it was remarked, employing ECRLC in making the ultra-lightweight and insulation, non-brittle reinforced sandwich panels, which are employed as non-load-bearing interior and exterior walls, is "a very simple and practical application of LFNLC in construction"*.
However, when ECRLC is used in making ultra-lightweight and low-height beams, usefully defining the relevant models and codes for ECRLC will have a great impact on the development and widespread use of this nonlinear composite in making ultra-lightweight, low-height bending elements. It can be taken into consideration also allowing for the discussions and analytical models relevant to nonlinear structures such as nonlinear porous elastic composites and the like [34, 35, 36, 37, 38].

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Statement

- Despite the official registration of the technology mentioned above as an invention by the author, there is no monopoly of this technology in practice. [The usage of ECRLC in construction [39] within the relevant standards and common equations has been approved and selected as a premier system by some academic and professional centers].
- Regarding the importance of the subject, this technology and the relating papers have been presented in these conferences too [40].

References

1. Esmaeili K. Elastic composite, reinforced lightweight concrete as a kind of resilient composite systems. *Internet J Innovat Tech Creativ Eng.* 2012; 2(8): 1-22. https://arxiv.org/abs/1510.03933. The Version Retrieved in 2019: https://www.academia.edu/3440017; https://sites.google.com/site/newstructure1 & https://sites.google.com/site/ecrlc1 (Att. No. 03) and https://www.scribd.com/document/11530978] [A similar paper in Persian is also available at https://www.scribd.com/document/11558652; https://sites.google.com/site/newstructure1 & https://sites.google.com/site/ecrlc1 (Att. No. 02)]
2. Li VC. Introduction to Engineered Cementitious Composites (ECC), In: Engineered Cementitious Composites (ECC). 1st ed., Springer (Berlin, Heidelberg, Springer-Verlag GmbH Germany, part of Springer Nature 2019), 419 pages; 2019. https://doi.org/10.2514/4.866821
3. Luković M, Huang Z, Hordijk D, Schlangen E. Strain hardening cementitious composite (SHCC) layer for the crack width control in reinforced concrete beam. Proceedings of the Workshop on Concrete Modelling and Material Behaviour in Honor of Professor Klaas van Breugel, Delft-Netherlands; 2018. https://repository.tudelft.nl/islandora/object/uuid:46ecefea-5019-47c0-8031-c975972397a0/datastream/OBJ/download
4. Şahmaran M, Li VC. Engineered cementitious composites. Can composites be accepted as crack-free concrete? *Transport Res Rec.* 2010; 2164: 1-8.
5. Esmaeili K. A short review on lightweight resilient composite (LRC). Proceedings of the 5th International Conference on Technology Development in Oil, Gas, Refining and Petrochemicals, The University of Applied Science, Tehran-Iran; 2021.
6. Shaaban IG, Shaheen YBI, Elsayed EL, Kamal OA, Adesina PA. Flexural behaviour and theoretical prediction of lightweight ferrocement composite beams. *Case Stud Construct Mater.* 2018; 9. https://www.sciencedirect.com/science/article/pii/S2214509518302377
7. Kaisha ABM, Jamil M, Raman SN, Zain MFM, Nahar L. Ferrocement composites for strengthening of concrete columns: a review. *Construct Build Mater.* 2018; 160: 326-340.
8. Aadithiya KV, Chandrasekaran DP. Review paper on usage of ferrocement panels in lightweight sandwich concrete slabs. *Int Res J Eng Tech.* 2017; 4(1): 69-73.
9. Hanif A, Lu Z, Sun M, Parthasarathy P, Li Z. Green lightweight ferrocement incorporating fly ash cenosphere based fibrous mortar matrix. *J Clean Prod.* 2017; 159: 326-335.
10. Yoo DY, Banthia N. Impact resistance of fiber-reinforced concrete - a review. *Cement and Concrete Composites.* 2019; 104: 103389.
11. Wei H, Wu T, Yang X. Properties of lightweight aggregate concrete reinforced with carbon and/or polypropylene fibers. *Mater.* 2020; 13(3): 640.
12. Rico S, Farshidpour R, Tehrani FM. State-of-the-art report on fiber-reinforced lightweight aggregate concrete masonry. *Adv Civil Eng.* 2017; ID 8078346.
13. Dixit A, Pang SD, Kang SH, Moon J. Lightweight structural cement composites with expanded polystyrene (EPS) for enhanced thermal insulation. *Cement and Concrete Composites.* 2019; 102: 185-197.
14. Lee JH, Kang SH, Ha YJ, Hong SG. Structural behavior of durable composite sandwich panels with high-performance expanded polystyrene concrete. *Int J Concr Struct Mater.* 2018; 12(21).
15. Laukaitis A, Žurauskas R, Kerien J. The effect of foam polystyrene granules on cement composite properties. *Cement Concr Compos.* 2005; 27(1): 41-47.
16. Adhikary SK, Rudzionis Z, Zubrus M. Investigations of the influence of polystyrene foamed granules on the properties of lightweight concrete. *J Appl Eng Sci.* 2019; 9(1): 248, 19-24.
17. American Concrete Institute (ACI). ACI Manual of Concrete Practice, ACI 523.1R-92, 2R-96, 3R-93, ACI (USA); 2017.
18. Tahuni S. Strength of Materials. 22th ed., An introduction to solid mechanics by Popov E, and Solid mechanics by Beyer F, Janson R. Parsaein Pub. (Iran); 2010.
19. Du H. Properties of Ultra-lightweight Cement Composites With Nano-silica. *Construct Build Mater.* 2019; 199: 696-704.
20. Rahimi H, Bina G, Esmaeili K. The effect of pozzolanic materials on the compressive strength of lightweight concrete. *J Agr Eng Res.* 2001; 2(6): 21-32.
21. Esmaeili K. A review on elastic composite reinforced lightweight concrete. Proceedings of International Conference on Advances in Cement-Based Materials and Applications to Civil Infrastructure (ACBM-ACI), Lahore-Pakistan; December 12-14 2007. [A similar paper in Persian has been published in Road & Building Journal (*Construct Architect Month J*). 2008; 50: 22-43. https://www.magiran.com/paper/551051 also available at

[DOI: 10.47176/sjfst.5.1.1]

https://www.scribd.com/document/11558652
https://sites.google.com/site/newstructure1 &
https://sites.google.com/site/ecrlc1 (Att. No. 02)]
22. Esmaeili K. Elastic composite, reinforced lightweight concrete and special EPS concrete. Compact disk [Register No. (of the earlier version) in the high council of informatics (Tehran, Iran): 100984]. 2004; 555 Pages.
23. American Concrete Institute. ACI Manual of Concrete Practice, ACI 318-95. ACI (USA); 2017.
24. Roberz F, Loonen RCGM, Hoes P, Hensen JLM. Ultra-lightweight concrete: energy and comfort performance evaluation in relation to buildings with low and high thermal mass. *Energ Build*. 2017; 138: 432-442. https://doi.org/10.1016/j.enbuild.2016.12.049
25. Esmaeili K. Lightweight and integrated construction, the pivotal tactic to increase the resistance and safety of constructions against earthquake. Road & Building Journal (*Construct Architect Month J*). 2018; 133: 39-48.
https://www.magiran.com/paper/1800118 The complete form of the paper has also been presented at: http://www.scribd.com/doc/11558528
https://sites.google.com/site/newstructure1 &
https://sites.google.com/site/ecrlc1 (Att. No. 01).
26. Esmaeili K. The non-brittle, insulation lightweight concrete plaster on the non-bearing foamed steel meshes (with six attachments). Version 2011, [in Persian]. <www.scribd.com>; 2011
[http://www.scribd.com/doc/32716377;
https://sites.google.com/site/newstructure1 &
https://sites.google.com/site/ecrlc1 (Att. No. 04).]
27. Huang Z, Wang F, Zhou Y, Sui L, Krishnan P, Liew JYR. A novel, multifunctional, floatable, lightweight cement composite. *Mater*. 2018; 11(10): 2043.
28. Viera LP, Carpio VA. Composite Cementitious Materials (CCM): State of the art, current situation and applications in civil engineering. [in Spanish] [Materiales Cementantes Compuestos (CCM): Estado del Arte, Situación Actual y Aplicaciones en la Ingeniería Civil]. *Rev INGENIO*. 2019; 2(2): 5-16.
https://doi.org/10.1016/j.jclepro.2019.119331
29. Zhou Y, Xi B, Sui L, Zheng S, Xing F, Li L. Development of high strain-hardening lightweight engineered cementitious composites: design and performance. *Cement Concr Compos*. 2019; 104: 1033702019.
30. Wang L, Aslani F, Hajirasouliha I, Roquino E. Ultra-lightweight engineered cementitious composite using waste recycled hollow glass microspheres. *J Clean Prod*. 2020; 249(119331).
https://doi.org/10.1016/j.jclepro.2019.119331
31. Wu M, Johannesson B, Geiker M. A review: self-healing in cementitious materials and engineered cementitious composite as a self-healing material. *Construct Build Mater*. 2012; 28(1): 571-583.
32. Olofinnade O, Chandra S, Chakraborty P. Recycling of high impact polystyrene and low-density polyethylene plastic wastes in lightweight based concrete for sustainable construction. *Materials Today: Proceedings*. 2021; 38(5): 2151-2156.
33. Wang R, Meyer C. Performance of cement mortar made with recycled high impact polystyrene. *Cement Concr Compos*. 2012; 34(9): 975-981.
34. Hodges DH. Nonlinear composite beam theory. American Institute of Aeronautics and Astronautics (USA). 2006; 304 Pages.
https://doi.org/10.2514/4.866821
35. Castañeda PP. Linear comparison methods for nonlinear composites. Nonlinear Homogenization and its Applications to Composites, Polycrystals and Smart Materials. Part of the NATO Science Series II: Mathematics, Physics and Chemistry Book Series, NAII, Vol. 170. Springer, Dordrecht. 2004; 247-268.
36. Castañeda PP, Suquet P. Nonlinear composites and microstructure evolution. *Mechanics for a New Millennium* [Springer, Dordrecht]. 2001; 253-274.
https://doi.org/10.1007/0-306-46956-1_17
37. Michel JC, Suquet P. Computational analysis of nonlinear composite structures using the nonuniform transformation field analysis. *Comput Method Appl Mech Eng*. 2004; 193(48-51): 5477-5502.
38. Miller L, Penta R. Homogenized balance equations for nonlinear poroelastic composites. *Appl Sci*. 11, 2021; 14: 66112021, 33 Pages.
https://doi.org/10.3390/app11146611
39. Esmaeili K. Simple use of elastic composite, reinforced lightweight concrete to improve the earthquake resistance of buildings on the large scale. The 7th International Conference on Civil, Structural and Seismic Engineering (by The Association of Technology Development Management and Engineering), Tehran-Iran, 19 Jun 2022. (in Persian) [http://cs.bcnf.ir. Available from https://civilica.com, etc]- [Also presented in the 6th International Conference on Applied Researches in Science & Engineering (by The Institution of Engineering and Technology; IET-London), Achen-Germany, 30 Mar 2022. (in Persian) [https://6carse.com. Available from https://civilica.com, etc]]- [Also accepted for the 6th Scientific Conference of Applied Research in Science and Technology of Iran (by The Armonasan Aso Systems Research Institute), Ilam-Iran, 16 Aug 2022. (in Persian) [https://scarsti.ir. Available from https://civilica.com, https://sid.ir, etc]]- [Also accepted for the 2nd International Conference on Architecture, Civil Engineering, Urban Development, Environment and Horizons of Islamic Art … (by Tabriz Islamic Art University, Iran University of Science and Technology, Mohaghegh Ardebili University, Alzahra University, Soore University, …), Tabriz-Iran, 8 Dec 2022. (in Persian)

[DOI: 10.47176/sjfst.5.1.1]

[https://www.2icacu.ir/. Available from https://civilica.com, https://isc.ac/, https://sid.ir, etc].
40. Esmaeili K. Lightweight flexible nonlinear composite (LFNLC)" and elastic composite, reinforced lightweight concrete as an LFNLC. The 6th International Conference on Applied Researches in Science & Engineering (by The Institution of Engineering and Technology; IET-London), Achen-Germany, 30 Mar 2022. (in English) [https://6carse.com. Available from https://civilica.com, etc]- [Also accepted for the 6th Scientific Conference of Applied Research in Science and Technology of Iran (by the Armonasan Also Systems Research Institute), Ilam-Iran, 16 Aug 2022. (in English) [https://scarsti.ir. Available from https://civilica.com, https://sid.ir, etc]]- [Also accepted for the 2nd International Conference on Architecture, Civil Engineering, Urban Development, Environment and Horizons of Islamic Art … (by Tabriz Islamic Art University, Iran University of Science and Technology, Mohaghegh Ardebili University, Alzahra University, Soore University, …), Tabriz-Iran, 8 Dec 2022. (in English) [https://www.2icacu.ir/. Available from https://civilica.com, https://isc.ac/, https://sid.ir, etc].

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https://doi.org/10.47176/sjfst..5.1.1