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An Introduction to Lightweight Flexible Nonlinear Composite (LFNLC) and Elastic Composite, Reinforced Lightweight Concrete (ECRLC) as the Cementitious LFNLC

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ABSTRACT

Here, a new class of high-performance composites, called "Lightweight Flexible Nonlinear Composites (LFNLC)", has been briefly introduced. This class of composites has its own structural and functional characteristics as *Nonlinear behavior in bending* and porous or porous-like texture. **-** Cementitious LFNLC is termed "Elastic Composite, Reinforced Lightweight Concrete (ECRLC)". The ECRLC provides lightweight beams with substantial strain capability, resilience modulus and toughness in bending, resulting in a considerable increase in bearing capacity while weighing significantly less. The failure mode in low-height and ultra-lightweight beams made of the ECRLC is not compressive and brittle. **-** This lightweight, flexible composite is a *non-monopolistic*, versatile and comparatively low-price material. Likewise, the virtues such as resilience and flexibility, workability, lightness, durability, and high formability are important in architecture. **-** In general, *lightweight and integrated construction* has a key importance in earthquake resistance. Therefore, *the ECRLC can be especially beneficial in earthquake-prone regions*. **-** Considering the flexibility and resilience of this formable system, it can also be used to build *non-brittle reinforced ultra-lightweight and insulation sandwich panels*, safe and lightweight guards, and *shock-resistant structures*. Likewise, they are utilizable in some infrastructures and *explosion-proof pieces with suitable behavior, resilience, and toughness*. **-** This work presents a practical method for *converting a rigid solid into a flexible material with lower density* or *increasing the elasticity of a flexible material while decreasing the density*. Essentially, this method entails creating a porous or porous-like texture in the material, reinforcing appropriately, and providing it with the necessary integrity. (For example, properly dispersing lightweight aggregates all over the reinforced, conjoined matrix can produce a porous-like texture.) By this process, *the resilience modulus and toughness in bending rise and the density reduces*. **-** This paper briefly discusses the functional and structural characteristics of LFNLCs, some applications, and *Reproducible* examples of the ECRLC.

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1. 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 LFNLCs is nonlinear behavior in bending, and the structural criteria have been presented later in this paper.

They are specifically made by "generating disseminated appropriate hollow pores and/or by dispersing suitable lightweight aggregates (such as 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, it is feasible to *considerably increase the modulus of resilience, the bearing capacity and the toughness in bending* along with *the significant decrease of the weight* as well as *the elimination of the possibility of failing in a brittle, compressive mode*. Through making these congruently (integratively) operating systems, the stated paradoxical virtues are concurrently 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, the LFNLC can be considered a flexible nonlinear structure with *high capability of strain*, modulus of elasticity and toughness in bending.

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

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

Considering the texture of the conjoined matrix of any LFNLC, the terms such as "Porous-like Flexible (Resilient) Composite" and "Porous-like Nonlinear Composite" could also be taken into consideration to point out this 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 clarified.

It is worth remarking that the term "Resilient Composite Systems (RCS)" has formerly been used, in the pertaining literature (Esmaeili, 2015), to refer to the class of composite structures here labeled "Lightweight Flexible Nonlinear Composite (LFNLC)". Considering some important differences among the high-performance composites classified as "Lightweight Flexible Nonlinear Composite (LFNLC)" and other resilient composites, such as those called "Engineered Cementitious Composite (ECC)" (Li, 2019) (Luković et al., 2018) (Şahmaran & Li, 2020), here, the term "Lightweight Flexible Nonlinear Composite (LFNLC)" has been used instead of the terms "Resilient Composite Systems (RCS)" (Esmaeili, 2015) and "Lightweight Resilient Composite (LRC)" (Esmaeili, 2021). [The term "Engineered Cementitious Composite (ECC)" usually refers to a particular class of High-Performance Fiber-reinforced Cementitious Composites (HPFRCC), also entitled "Strain Hardening Cement-based Composites (SHCC)". It has also been popularly termed "Bendable Concrete (Flexible Concrete, Foldable Concrete)" (Li, 2019) (Luković et al., 2018) (Şahmaran & Li, 2020).

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

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

However, it is also feasible to merge these technologies into one integrative system. For instance, by properly reinforcing the structure named the ECC with an appropriate lattice (such as a fitting mesh) along with generating disseminated appropriate hollow pores and/or dispersing suitable lightweight aggregates throughout the structure, we can obtain a kind of the LFNLC. *The flexibility of this lighter structure, with* *high modulus of resilience and toughness in bending, will be greater than that of the mentioned ECC (with a higher density). In this way, the weight can be reduced, and the performance can be improved depending on the case.*

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

Further clarification of some discussions formerly presented in the pertaining literature (Esmaeili, 2015), and the necessary correction, modification and improvement of some topics regarding the subject necessitated this comprehensive paper. The present paper substantially includes the essence of the former literature (Esmaeili, 2015) in an upgraded form.

2. Structural and Functional Criteria of LFNLCs

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

2.1. Structural Criteria and Essential Components:

In general, any LFNLC includes the following components. 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 a lightweight composite, as the nonlinear behavior in bending, in practice.

A) Skeletal mesh: Considering the Ferrocement technology (Aadithiya, 2017) (Hanif et al., 2017) (Kaisha et al., 2018) (Shaaban et al., 2018), steel wire meshes are the examples of such reinforcement. If expedient, some suitable nonmetal meshes, such as those made of Fiber Reinforced Polymer (FRP), can be utilized too. In any case, "the elasticity modulus 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 ought to be used.

B) Fibers: Various types of fibers with acceptable elasticity can be used in LFNLCs. For instance, polymer fibers, like Polypropylene Fibers (as a widely used material, with good resilience to impact), are among such fibers (Nadh & Muthumani, 2017) (Rico et al., 2017) (Wei et al., 2020) (Yoo & Banthia, 2019).

In any case, similar to some of other fiber-reinforced materials, "the elasticity modulus and the elastic strain limit in tension of the fibers" must be more than "those of the binding substance of the system when containing the same lightweight aggregates and/or the hollow pores (but not containing the fibers)".

Likewise, the presence of the fibers with a length greater 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 effective fiber reinforcement.

C) *Conjoined* (well-integrated, congruent) matrix *also having disseminated appropriate pores and/or dispersed suitable lightweight aggregates*: [Here, the term "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 of *the presence of the pores and/or the lightweight aggregates throughout the matrix to reach a porous or porous-like texture*, this *lightweight* matrix cannot be considered a homogeneous 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 lightweight aggregates with a 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 the LFNLC can mainly include polymeric materials and/or non-polymeric materials (such as C-S-H crystals) as the binding substance. Thus, we can have "Polymer-based or Polymeric Lightweight Flexible Nonlinear Composite (Po-LFNLC)" and "Non-polymer-based LFNLC" like "Cement-Based or Cementitious Lightweight Flexible Nonlinear Composite (Ce-LFNLC)" (which is also entitled "Elastic Composite, Reinforced Lightweight Concrete, ECRLC").

♦ *An example of lightweight, fiber-**reinforced** conjoined matrix used in the ECRLC*:

A special fiber lightweight concrete also containing the beads of expanded polystyrene (EPS) is a good *example* of the substances that can be used as the lightweight fibrous matrix of the ECRLC.

In general, utilizing the EPS beads, as an ultra-lightweight aggregate with very little water absorption, to lower the concrete density is a known method mentioned and discussed in much related literature; for instance: (Abed, 2019) (Adhikary et al., 2019) (American Concrete Institute (ACI), 2017) (Babu & Babu, 2003) (Dixit et al., 2019) (Jhansi, 2023) (Kekanović et al., 2014) (Khatib et al., 2019) (Kumar & Baskar, 2015) (Laukaitis et al., 2005) (Mishra, 2020) (Moon, 2021) (Nadh & Muthumani, 2017) (Prasittisopin et al., 2022) (Sun, 2022) (Tayal et al., 2018) (Vilches, 2014). Fresh polystyrene beads and/or recycled polystyrene beads ("eco-beads" or "eco-beans", produced by appropriately crushing waste polystyrene via a suitable machine) are employed in the EPS concretes. Such a lightweight concrete, also labeled Polystyrene Aggregate Concrete (PAC), with the density of about or less than 800 kg/m^3 is ordinarily used for insulation as well.

A special fiber EPS concrete can fittingly be utilized as the matrix of the ECRLC as well. 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 curve of the fibrous EPS concrete, stated above, in compression has been shown in figure 1 (Esmaeili, 2004) (Esmaeili, 2007) (Esmaeili, 2015).

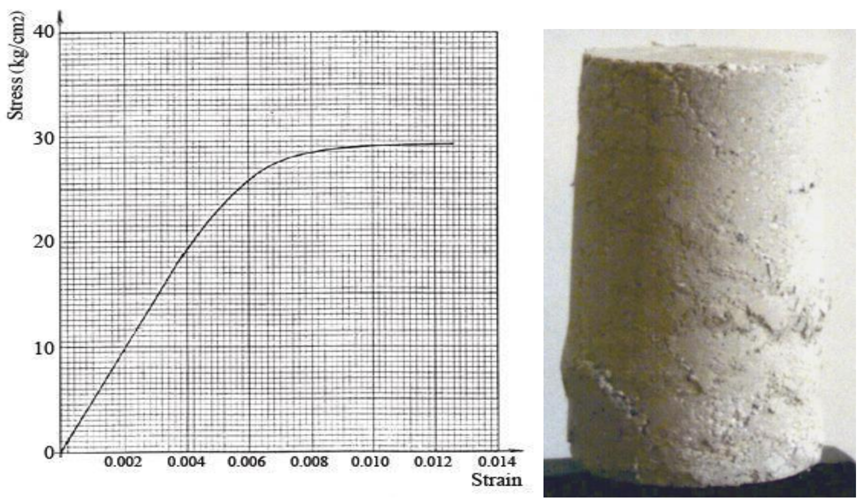

Figure 1. The Stress-Strain Diagram of a Special Fiber-reinforced EPS Concrete, Also Containing the EPS Beads, in Compression

- 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 the volume of the concrete. [Here, n*o 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 usual sense as a certain and exact value, cannot be determined. (ε_{cu} ↑) [Likewise, the Stress Block Coefficients (α and β) are high.]

2.2. Functional Criteria:

As stated formerly, in the organized system called the LFNLC, the amount and the manner of the use of the main elements 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 LFNLCs, the main strategy to enhance the modulus of resilience in bending is *to increase the strain capability (strainability) of the system in bending within the elastic limit*. This is achieved by *generating appropriate hollow pores and/or utilizing suitable lightweight aggregates, dispersed throughout the methodically reinforced conjoined matrix.* This will allow for internal deformations in the matrix to occur *in a particular manner* during bending. (This particular manner of internal deformations occurrence can lead to better distribution of the strains and the stresses all over the system and the more strain capability of the beam in bending.)

Obviously, only dispersing the suitable lightweight aggregates and/or generating the appropriate hollow pores throughout the matrix, by itself, not only could not result in the stated goals but also would cause 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 appropriate 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 more appropriate distribution of the tensile strains and stresses all over the system. This distribution pattern of the stresses and the strains all over the structure increases the modulus of resilience and endurance in tension and bending and enhances the flexibility by withstanding the strains.

As stated, dispersion of the suitable lightweight aggregates and/or generation of the appropriate hollow pores all over the reinforced conjoined matrix, provides *the necessary possibility for occurring of internal deformations in the matrix during bending "in a particular manner"*. This particular manner of internal deformations occurrence leads to reduced accumulation and concentration of internal stresses at certain points in the matrix during bending. This results in improved absorption and control of the stresses, and enhances the beam's strain capacity, particularly within its elastic limit.

Through bending, internal deformations, in the matrix, occur in two main forms: I) The in-compression layers experience a relative rise in height, especially in the upper parts of the beam. (It means the conversion of some internal compressive stresses to internal tensile stresses, perpendicular to the mentioned internal compressive tensions, in the in-compression layers.) II) On the other hand, the in-tension layers experience a relative reduction in height (thickness), especially in the lower parts of the beam. (It means the conversion of some internal tensile stresses to internal compressive stresses, perpendicular to the stated internal tensile stresses, in the in-tension layers.

In the under-bending sections of LFNLCs, the deformations occurring in "the adjoined layers perpendicular to the applied load direction" during bending 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 LFNLCs, the mentioned internal deformations in the beam during bending result in the tendency of the neutral axis of the beam to shift downwards. (This tendency of the so-called neutral axis to move downwards is contrary to the shift of the neutral axis of ordinary reinforced concrete beams upwards during bending. Upon a basic *assumption* of the flexural theory, *"the sections perpendicular to the axis of bending that are* *plane before bending remain plane after bending"* (Tahuni, 1991).) In these flexible composite structures, against the fundamental assumption of the flexural theory and the related kinematic and geometrical equations (discussed in solid mechanics and strength of materials), the strain changes in the beam height during bending are *principally nonlinear*. (In other words, 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 the LFNLC; those relations and equations lose their meaning and applicability in this case.

Through the occurrence of the mentioned internal deformations in the methodically supported lightweight, conjoined matrix of the structure during bending, the stresses are more distributed and absorbed, and *"the rate of the accumulation and rise of internal stresses at certain points of the matrix, during bending," lessens*. All in all, by better withstanding the strains during bending, *more strain capability* of the beam made of the LFNLC in flexure is provided.

Naturally, the ECRLC, as a particular class of complex materials, displays anisotropic properties.

3. "Elastic Composite Reinforced Lightweight Concrete (ECRLC)" as a Kind of Lightweight Flexible Nonlinear Composite (LFNLC)

As 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 example of the SCM that can affect various aspects of concrete (Babu & Babu, 2003) (Du, 2019). (Rice husk ash, as a type of pozzolanic material (Rahimi, Bina, & Esmaeili, 2001), is another instance of the SCM.)]

The ECRLC can be considered a Cementitious Nonlinear Composite. In view of the particular 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 the ECRLC" are overall more than "those of similar ordinary reinforced concrete beams".

The ECRLC density is less than 1920 kg/m^3 as well. The presence of the hollow pores and/or the lightweight aggregates decreases the density of the material in total. By employing the ECRLC, we can also easily reach a very lightweight reinforced concrete with densities of *about or less than 800 kg/m^3*. [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) (American Concrete Institute (ACI), 2017).]

By utilizing the ECRLC, some substantial problems in using lightweight concrete, such as 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 removed. *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 the LFNLC, the results of flexural tests performed on the slabs made of a kind of the ECRLC, *with and "without" supplementary tensile steel bars*, in a method similar to ASTM E 72 are noticeable (Esmaeili, 2004) (Esmaeili, 2007) (Esmaeili, 2015).

In the analysis of the slabs made of a kind of the ECRLC (with and *without* the supplementary rebar) to calculate the nominal strength in bending via the method called the "Ultimate Strength" (American Concrete Institute (ACI), 2017) (Tahuni, 1991), 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. [It is worth remarking that 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 fundamental assumption of the flexural theory (Tahuni, 1991).]

Likewise, the actual amounts of "the cracking moment (M_{cr})", "the modulus of resilience ($u = ½ \sigma_y . \varepsilon_y$)", 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 fundamental assumption of the flexural theory) mathematically tends to infinity (∞) and the stress block height is supposed to be equal to zero, the actual strength, in the flexural test, in practice is still higher than the M_n.

Indeed, in view of the actual behavior of the slabs made of a kind of the ECRLC through bending, despite the large increase in the tensile forces in the slab in bending, even much more than what is called "compressive block strength" *obtained from the routine relations & equations based on the said fundamental assumption of flexure* (American Concrete Institute (ACI), 2017) (Tahuni, 1991), the strain of the slab still continues until reaching the actual maximum capacity of strain.

As mentioned, the behaviors of the components of this integrated system in bending are compatible (consistent) with each other. (Of note, some researchers have also stated that certain EPS concretes, unlike ordinary concrete, are compatible with steel, which could be evident in the notable behavior of the beams made of the steel reinforced EPS concrete in bending (Kekanović et al., 2014).)

In this way, *making more use of the strength capacity of the tensile reinforcement* has been possible. It is due to the occurrence manner of the deformation of the beams through bending and the greater 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 has 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 preclude the 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 fundamental assumption of the flexural theory as well (American Concrete Institute (ACI), 2017) (Tahuni, 1991).] In any case and as a rule, the beams made of the LFNLC do not fail in bending in a flexural compression mode.

"A Reproducible, simple example of the lightweight flexible slab made of the ECRLC", additionally reinforced with supplementary tensile steel bars as accessory supportive reinforcement, has been shown in *figure 2* in detail (Esmaeili, 2004) (Esmaeili, 2007) (Esmaeili, 2015). [Here, "*the Mix Design" of the special pozzolanic fiber-reinforced lightweight concrete used as the lightweight, fibrous conjoined matrix of the said composite structure* and all details required for any replication of the tests have been presented too.]

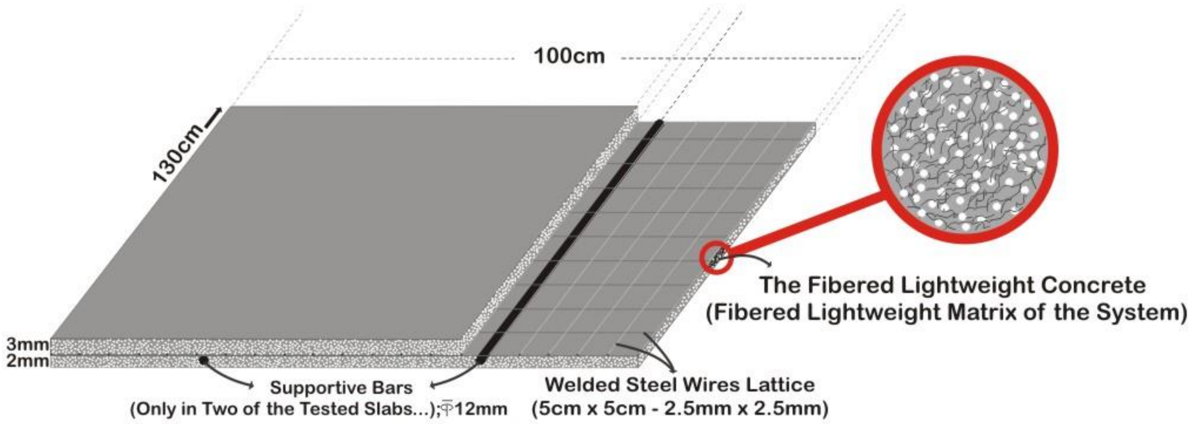

Figure 2. ***A "Reproducible", Simple Example* of the Lightweight Flexible Slab Made of the ECRLC (as a Kind of the LFNLC), Additionally Reinforced With Supplementary Tensile Steel Bars**

- 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 dispersed 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/m³, 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/m³; 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/m³ (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 m³. [If finer beads, e.g. with $D_{50} \approx 1$ mm, are employed, the f'_c of the lightweight concrete used in making the structure will be increased.] [Naturally, the high difference between the apparent density of the EPS granules and their true density 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 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 the slabs in very high bending loads occurred owing to the rupture of the wires from such weak points.

- It is worth remarking that the presence of any supplementary element, such as the tensile steel bars shown above, is *not an essential condition* to consider a structure as the LFNLC or the ECRC. Here, considering the tests performed on the slabs, which some of them had been additionally reinforced with the supplementary bars, the supportive bars used 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 that the tests are performed on the slabs having and those *not* having the supplementary reinforcement, such as bending steel bars, under similar conditions.

4. Applications

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

4.1. Some Applications in Building Industry:

LFNLCs can be employed in constructing the elements subject to bending, shock, and vibration. This *versatile material* can be utilized in making roofs, floors and decks, walls and partitions, multi-floor parking garages, etc.

Typically, ordinary reinforced ultra-lightweight concretes are dramatically *brittle* (Nadh & Muthumani, 2017) (Rico, Farshidpour, & Tehrani, 2017); 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 (such as 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 ECRLCs, this substantial problem can be removed. *This special merit of the ECRLC has a crucial importance especially in seismic areas.*

Lightness has a decisive role in thermal insulation and *saving energy* as well (American Concrete Institute (ACI), 2017) (Esmaeili, 2011) (Esmaeili, 2018) (Esmaeili, 2022b) (Roberz et al., 2017).

In addition to *the speed and ease of constructing*, lightness is a significant *economic advantage*, especially in constructing tall buildings such as towers. By employing LFNLCs, the weight can be considerably decreased. (For example, by utilizing the ultra-lightweight and flexible insulation materials instead of some conventional materials, the total weight has been reduced to approximately one-sixth in some cases.) In this way, the total cost of building construction can be lessened as well.

It can also be used for the *rehabilitation* and strengthening of some old structures.

In general, the following virtues have high importance in *architecture* too: lightness, durability, resilience and flexibility, workability and formability (such as *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 the LFNLC and the possibility of applying any expedient supplementary elements and materials, the lightweight fibrous matrix of the 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 a kind of the 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 utilized concomitantly with LFNLCs*. 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, *depending on the case*, can improve the integrity, strength, and duration of the matrix and enhance the overall behavior and resistance of the structure especially in bending and to the severe impact and continual dynamic loads. However, the supplementary elements and materials are not essential to consider a system as an LFNLC.

♦ *Using the 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. The ECRLC, as a kind of the LFNLC, can be utilized to broadly implement this key tactic to withstand seismic loads (Esmaeili, 2004) (Esmaeili, 2007) (Esmaeili, 2011) (Esmaeili, 2015) (Esmaeili, 2018) (Esmaeili, 2022b).

In general, the following items 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 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.

It is worth remarking that applying the stated practical method to make the LFNLC, particularly such as the ECRLC, as well as using ECRLCs in construction has been accomplished for the first time, in the first half of 2000s, in Iran (Esmaeili, 2004) (Esmaeili, 2007) (Esmaeili, 2011) (Esmaeili, 2015) (Esmaeili, 2018) (Esmaeili, 2022b). It was done especially in view of the high risk of earthquake in Iran, which is 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 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 the ECRLC, as a kind of the LFNLC, in making ultra-lightweight and insulation, non-brittle reinforced sandwich panels:*

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

A kind of the LFNLC that is termed the 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 the ECRLC, as a comparatively inexpensive material, in making such *"non-brittle ultra-lightweight panels"* that are employed as non-load-bearing interior and exterior walls is *"a very simple and practical application of LFNLCs"*.

These panels can be *cast-in-place* or precast.

. 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 considering the related factors. Many times, Portland cement type II (modified) could be a good choice.] [If expedient, and depending on 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, the expanded polystyrene (EPS) beads, the additives, and the water-to-binder ratio in the mix design (Esmaeili, 2004) (Esmaeili, 2007) (Rahimi, Bina, & Esmaeili, 2001).]; 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 very small amount of silica fume, before adding to the mix, for better separation and dispersion of the fibers.]; and Expanded Polystyrene (EPS) Beads ($D_{50} \leq 3.2$ mm) up to 1 m^3. [In general, for such applications, the EPS beads with the true densities as low as possible are *economically* preferred. Likewise, using the beads with the sizes as small as possible (such as the EPS beads labeled fine and 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 as well.] [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 (which has a so-called porous-like texture).] [All of the ingredients ought to be *well mixed*, e.g., for at least 15 minutes. The slump of the relatively sticky fibered cementitious paste obtained in this way is about zero. It is *a formable and easily molded material* that can easily be applied on the surface. (The oven-dry density of this example of the very lightweight and insulation fiber-reinforced EPS concrete is approximately 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 mold between the two layers of the steel wire meshes) can 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 stated 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, are 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. In 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 approximately 50-65 kg/m^2.]

Allowing for a construction system known as 3D panel technology (Saravanan & Mohanraj, 2018) (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 (Esmaeili, 2004) (Esmaeili, 2007) (Esmaeili, 2011) (Esmaeili, 2018) (Esmaeili, 2022b).)

In general, the following items 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, such as stucco or plaster, that can be adequate for finishing the surface; usable in-door space; etc. (Some simple instances of easily utilizing ECRLCs and the mentioned special fiber EPS concrete, sometimes called *"special fiber Betastyrene"*, in construction have been shown in figure 3 (Esmaeili, 2004) (Esmaeili, 2007) (Esmaeili, 2011) (Esmaeili, 2018) (Esmaeili, 2022b).)

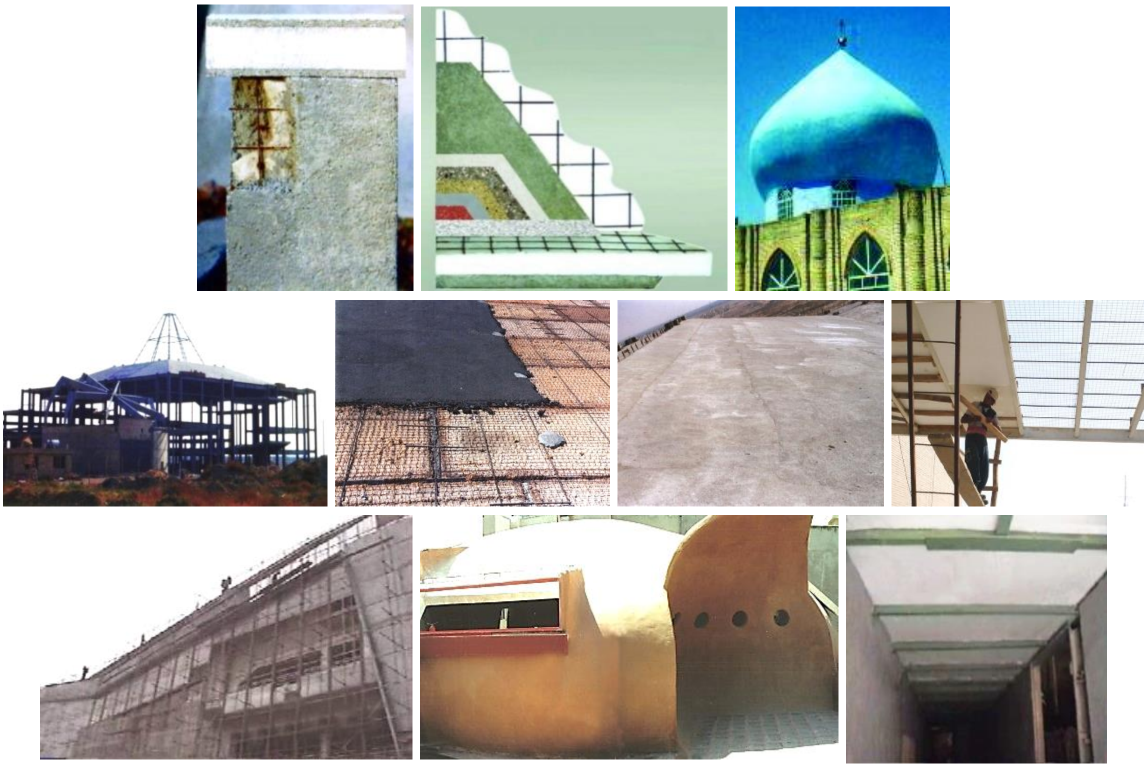

Figure 3. Some Simple Instances of Easily Using ECRLCs and the Mentioned Special Fiber EPS Concrete in Construction

4.2. Some Other Feasible Applications:

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

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

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

[It is worth remarking that a noteworthy type of "Floatable, Lightweight Cement Composite (FLCC)", as a kind of reinforced ultra-lightweight concrete, has been presented by some researchers (Huang et al., 2018). Anyhow, in consideration of the materials used in that type of the FLCC, such as the matrix constituents and the inelastic glass microspheres utilized as the lightweight aggregates, its overall behavior in bending cannot be principally nonlinear; it cannot be considered an LFNLC.]

5. Discussion

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

5.1. 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 simply involves "creating what is called the porous or porous-like texture" along with "appropriately reinforcing the material" and "providing the essential integrity". Creating the porous or porous-like texture is done by "generating disseminated appropriate hollow pores" and/or "dispersing suitable lightweight aggregates (such as the EPS beads)" throughout the reinforced matrix. By this process, 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 elimination 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. The LFNLC is a lightweight methodically reinforced, flexible nonlinear material with *an especially high specific modulus of resilience and toughness in bending*. *(In LFNLCs, 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 cementitious composite with more flexibility and performance* even compared with the ordinary engineered cementitious composite (ECC).

The ECRLC, as a cement-based LFNLC, is a versatile, novel material. Likewise, in comparison with some other high-performance composites and materials, the ECRLC is comparatively low-price. 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*, as well.

5.2. Further Work and Studies Proposed for the Future:

Considering the development history of "Cementitious Composite Materials (CCM)" (Sikora & Chung, 2020) (Viera & Carpio, 2019) (Xiao et al., 2021), work on the FLNLC structures, especially those having a very low density, can be advanced and eventually go *beyond the cement-based composites*. Anyway, developing these advanced materials and their applications in various fields demands further work in a variety of fields within an interdisciplinary approach.

For this purpose, some related technologies, such as ferrocements (Aadithiya, 2017) (Hanif et al., 2017) (Kaisha et al., 2018) (Shaaban et al., 2018) and engineered cementitious composite (ECC) (Bai et al., 2020) (Deng et al., 2023) (L. Wang et al., 2020) (Wu et al., 2012) (Xiao et al., 2021) (Zhou et al., 2019) can be taken into consideration as well. It is also possible to merge some related technologies into one integrative system.

5.2.1. Likewise, the effects of using the following substances on the qualities of the LFNLC can be studied: various lightweight aggregates such as High Impact Polystyrene (HIPS) (Mahmood & Kockal, 2020) (Olofinnade et al., 2021) (R. Wang & Meyer, 2012), various kinds of waste and recycled materials (Abed, 2019) (Altera et al., 2020) (Guo et al., 2018) (Jhansi, 2023) (Kan & Demirboğa, 2009) (Kekanović et al., 2014) (Khatib, Herki, & Elkordi, 2019) (Kočí et al., 2022) (Kumar & Baskar, 2015) (Mahmood & Kockal, 2020) (Okeyinka et al., 2015) (Olofinnade, Chandra, & Chakraborty, 2021) (Tayal et al., 2018) (Vilches, 2014) (L. Wang et al., 2020) (R. Wang & Meyer, 2012) such as modified waste expanded polystyrene

(MWEPS or MEPS) (Kan & Demirboğa, 2009) (Mahmood & Kockal, 2020) and some other kinds of lightweight elastomeric aggregates; varied amounts, kinds, forms and sizes of fibers (like nanofibers, microfibers, and larger fibers) and hybrid fiber reinforcement (Goel et al., 2022) (Pakravan & Ozbakkaloglu, 2019); some hydrophilic fibers and substances; types of curing such as internal curing (Al Saffar et al., 2019) (Karim, 2021) (Ma et al., 2019) (Xu et al., 2021) (Yang et al., 2021); 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) (El-Kady et al., 2022) (G. Feng et al., 2022), etc); any other materials that could enhance the integrity, elasticity and resilience of the system.

By the same token, the results of some studies concerning what is called High-performance Expanded Polystyrene Concrete (HPEPC), produced by mixing the ultra-high-performance concrete matrix and expanded polystyrene beads, could be considered as well. This composite material is also used to make composite sandwich panels (Lee et al., 2018).

In general, allowing for the promising results of the work about the durability of a modified form of the EPS concrete *under dynamic cyclic loading* (Shi et al., 2016), using various types of lightweight aggregates, pore-generating materials, binding materials, fibers, and meshes within the framework of the LFNLC can also be taken into consideration.

Of note, utilizing the EPS geofoam to make pavement blocks has been put forward by some researchers as well (Bhuinyan et al., 2019).

Another idea is increasing the total amount of the very small pores 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, etc) as well as employing the expedient blended fibers (also including the fibers with small and/or very small sizes) and paying attention to the water absorption properties of the final product. (Of note, the nanopore-rich cement-based porous materials based on colloidal silica sol, also known as colloidal silicic acid, have also been presented by some researchers (Lu et al., 2021).)

5.2.2. Considering the experiences and discussions in the final resistance of structures to shock waves, such as blasts, and some related topics (Anas et al., 2023) (Mohammadi Hooyeh et al., 2023) (Mohammadi et al., 2020) (Ramezanali et al., 2022) (Shabani et al., 2023), utilizing the LFNLC, like the ECRLC in appropriate forms, can be considered a suitable and practical choice in many cases. This system, with significantly high specific modulus of resilience and toughness in bending, can effectively absorb kinetic energy and mitigate the pressure of blast and shock waves. It is recommended to carry out the relevant studies to optimize the system for use as blast protection walls, explosion guards, and any sacrificial claddings *in specific cases*.

5.2.3. In view of the binder amount and the reinforcement, such as fibers, used in the ECRLC, and considering the capability of self-healing in the ECC structures (Wu, Johannesson, & Geiker, 2012), it is proposed that the self-healing capability of the ECRLC structures be studied too.

5.2.4. One of the priorities to promote broadly using LFNLCs in making beams is presenting the relevant models & equations for a true analysis of the behavior of the LFNLC structures in bending. To date, in 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 the ECRLC structures as well. (Anyhow, considering the particular behavior of the LFNLC structures in bending, there is no need to calculate 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 the ECRLC in flexion have been much higher than the nominal values obtained from the common equations. The equations routinely employed for the analysis of ordinary reinforced concrete beams are based on the fundamental assumption of the flexural theory, which is not the case with the LFNLC beams.

When an LFNLC such as the 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 for any specific equations for a true analysis of such nonlinear structures in bending. As mentioned, *employing the ECRLC in making the ultra-lightweight and insulation, non-brittle* *reinforced sandwich panels that are employed as non-load-bearing interior and exterior walls is "a very simple and practical application of LFNLCs in construction".*

However, when the ECRLC is used in making ultra-lightweight and low-height beams, usefully defining the relevant models and codes for the 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 (Castañeda, 2004) (X. Feng et al., 2022) (Hodges, 2006) (Michel & Suquet, 2004) (Miller & Penta, 2021) (Ponte Castañeda & Suquet, 2001).

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Conflict of Interest

There is no conflict of interest to declare.

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Declaration

Notwithstanding the official registration of the technology mentioned above as an invention (in Iran) by the author and the approvement of the system by some relevant organizations (as The Iranian Research Organization for Science and Technology (IROST) through the evaluation process of The National Foundation of Elites and The Iran National Science Foundation (INSF) and despite publishing a patent application by the USPTO regarding the RCS, *there is no monopoly of this technology in practice*. All information concerning this technology has been disclosed, by the author, through open-access media for public use. [The usage of the ECRLC in construction within the relevant standards and common regulations (Esmaeili, 2011) (Esmaeili, 2018) (Esmaeili, 2022b) (Saravanan & Mohanraj, 2018) within has also been approved and selected as a premier system by some academic and professional centers (as Tehran Construction Engineering Organization).]

Regarding the importance of the subject, this topic and similar discussions have also been presented, by the author, in some meetings as: (Esmaeili, 2007) (Esmaeili, 2021) (Esmaeili, 2022a).

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