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Properties of Fiber-Reinforced Structural and Non-Structural Ultra Lightweight Aggregate Concrete

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Abstract – *This study is focused on studying the effect of synthetic short fibers on the mechanical properties of ultra lightweight aggregate concrete (ULWAC). Both non-structural and structural fiber-reinforced ULWAC were considered. The data were collected from different studies, including 15 design papers submitted by universities in the USA and Canada to ASCE National Concrete Canoe Competition (NCCC) with 23 different ULWAC mixes. The data were analyzed, and new modified equations to determine the modulus of elasticity and modulus of rupture were proposed that could improve the accuracy of the current ACI equations. The statistical parameters of fiber reinforced structural ULWAC were determined, and high cost was associated with this type of concrete. Ductility indices for plates and beams, that have the capability to exhibit strain-hardening prior to failure, were calculated using energy-based method, and they were above the minimum required value of 3. Finally, a new model was proposed to predict the complete stress-strain behavior of fiber reinforced ULWAC under axial compression.*

Keywords: *Ductility, Elasticity, Fibers, Rupture, Structural Ultra Lightweight Concrete*

Nomenclature

E_c	modulus of elasticity of concrete
E_e	elastic energy computed from load-deformation curve
E_t	total energy computed from load-deformation curve
f_c	cylinder compressive strength corresponding to any compressive strain ε
f_c'	cylinder compressive strength
f_r	theoretical modulus of rupture of concrete
f_r^*	experimental modulus of rupture of concrete
V_f	% volume fraction of fiber
Ω	ratio of experimental to theoretical moduli of elasticity
Ψ	mathematical expression related to modulus of rupture
χ^2	Chi-square goodness of fit
ε	compressive strain corresponding to any compressive strength f_c
ε_{cu}	ultimate compressive strain
ε_0	strain corresponding to the peak stress
γ_c	density of concrete
λ	aggregate factor
μ_E	ductility index

I. Introduction

Ultra lightweight aggregate concrete (ULWAC) has been used primarily in civil engineering construction field as non-structural members in concrete blocks, bricks, and wall panels. Reduction of the dead load weight of a structure could result in a decrease in the cross-section of the structural elements, such as beams, columns, and foundations. It could also reduce the reinforcing steel of reinforced concrete structures [1]. Furthermore, this reduction in weight of a structure can decrease the risk of earthquake damage to the structure, since the earthquake forces and the mass of structural components are proportional [2]. Among other advantages of using ULWAC are: excellent thermal insulation, fire resistant and sound insulation.

Typically, normal weight concrete (NWC) has a density between 2155 and 2555 kg/m^3 and a compressive strength between 17 and 55 MPa at age 28 days [3], while structural lightweight concrete (SLWC) has a density between 1120 and 1920 kg/m^3 and a minimum compressive strength of 17 MPa [4]. In this study, concrete with a dry density between 600 and 1050 kg/m^3 and a compressive strength less than 17 MPa will be referred to as non-structural ULWAC, while structural ULWAC (SULWAC) will be referred to concrete with a

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density less than 1050 kg/m^3 and a minimum compressive strength of 17 MPa.

Lightweight aggregate (LWA) is the key factor in making ULWAC. Although recycled expanded glass is the most common type of LWA, other materials, such as expanded poly-lactic acid and synthetic foam were used [5],[6]. Sustainable and durable fiber-reinforced ULWAC (FRULWAC) with a very low compressive strength between 0.5 and 3.6 MPa and a density between 400 and 795 kg/m^3 was made using cement, sand, synthetic foaming agent, supplementary cementitious materials and polypropylene (PP)/carbon fibers [6]. Cement, high-strength glass LWA, fly ash, silica fume, polyethylene fibers and high-range water reducer were used to develop ULWAC with a fresh density between 930 and 940 kg/m^3 and a compressive strength between 26.9 and 31 MPa [7]. Industrial by-products as alkali activation (geopolymer), NaOH as the alkali activator, and recycled glass lightweight aggregate were used in making sustainable ULWAC with a maximum compressive strength of 10 MPa and dry a density between 800 and 950 kg/m^3 [8]. ULWAC was developed using recycled glass as LWA with a compressive strength of 10 MPa, dry density between 650 and 700 kg/m^3, very low thermal conductivity and excellent resistance against water penetration [9]. Recycled expanded glass LWA and PP fibers were used to make ULWAC, with a compressive strength of 16 MPa and a dry density of 750 kg/m^3 [10]. ULWAC with a density between 1001 and 1073 kg/m^3, compressive strength between 1.1 and 5.8 MPa at age 7-days, and improved workability and flexural strength were reported, using perlite LWA and rubber latex [11]. FRULWAC with a density of 760 kg/m^3 and a compressive strength of 6 MPa were reported [12].

In this study, the term high-performance concrete (HPC) is referred to concrete that has the capability to exhibit strain-hardening prior to failure. However, HPC is also used to refer to concrete with special properties, such as high compressive strength, high modulus of elasticity, ease of placement and consolidation, etc.

The addition of short fibers, in relatively large amounts, to the concrete mixture, would result in an enhanced strain-hardening due to bridging mechanism where the load is transferred back and forth between the cement matrix and the fibers until the fibers pull out or rupture leading to the final failure of the composite [13]. Fiber-reinforced concrete (FRC) with noticeable strain-hardening response, has shown to be an ideal application for blast protective structures [14],[15]. Polyvinyl alcohol (PVA) fibers and engineered LWA were used to develop high-performance lightweight aggregate concrete (LWAC) and ULWAC plates that showed high flexural strength, high flexural ductility, and excellent toughness [16]. Impressive strain-hardening capacities were observed, when PVA fiber-reinforced SULWAC (FRSULWAC) beam specimens made with engineered LWA, were tested experimentally [Appendix A-11]. The use of FRSULWAC in structural component members will improve the flexural fatigue strength [17].

In this paper, an attempt to study and identify the effect of synthetic short fibers on the mechanical properties of FRULWAC was made. Data collected from different design papers were analyzed, and mathematical expressions to predict the modulus of elasticity and modulus of rupture were developed. Ductility indices for ductile FRULWAC plates and beams were calculated using energy-based method. Finally, a new mathematical model to predict the complete stress-strain behavior for FRULWAC was proposed based on several collected stress-strain curves of fiber reinforced concrete under axial compression.

II. Materials

A wide range of materials can be used to produce high-performance FRULWAC. Each type of the material has a different effect on the overall mechanical properties of the composites. In this study, the majority of the used data were collected from 15 different design papers submitted by universities in USA and Canada to ASCE *National Concrete Canoe Competition* (*NCCC*) (Listed in Appendix A) with a total of 23 FRULWAC mixes. The main materials used in making most of these mixes are as follows:

- Portland cement Type I.
- A combination of supplementary cementitious materials, such as slag, VCAS pozzolans, silica fume, and fly ash.
- A combination of engineered spherical glass LWA of different sizes and physical properties, such as recycled glass spheres (Poraver®) and hollow microsphere glass bubbles (3M™).
- A combination of different admixtures, such as high-range water reducer and air entrainer.
- PVA fibers of length ≥ 6.35 mm.

However, the addition of air entrainer admixture and excessive fibers to the concrete mix would result in a reduction in the compressive strength [18], [19]. Fig. 1 shows aggregate gradation curves for some FRULWAC mixes and fine aggregate grading limits specified in ASTM C33/C33M-18 [20]. It can be seen that some of the mixes fall in the range of ASTM specification limits and some don’t. FRULWAC doesn’t slump as much as NWC due to lower aggregate specific gravity resulting in low workability [21]. It is worth to mention that the production process of ULWAC is associated with several technical difficulties. Among these difficulties are the excessive overheating of concrete during the early hydration stage caused by its self-insulating properties, which can be solved by a careful selection of binder type and content, and poor compaction due to the low density of concrete [22], [23].

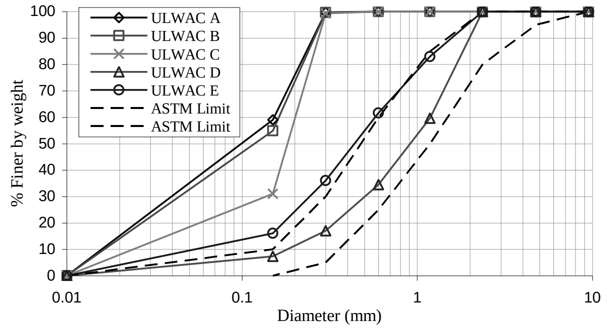

Fig. 1. Aggregate gradation curves of LWA for some FRULWAC mixes

III. Fiber-Reinforced Structural Ultra Lightweight Aggregate Concrete

With the advances of civil engineering and construction materials, it has become possible to produce very lightweight concrete composites with structural properties. Fig. 2 shows the cylinder compressive strength and dry density of 10 different FRSULWAC mixes collected from 7 design papers (listed in Appendix A and labeled with letter S). Table B-I shows the mechanical properties of these mixes, while Tables B-II and B-III (all located in Appendix B) show the LWA and cementitious materials proportions by weight. It was found that the ratio of LWA to cementitious materials, by weight, fall in the rage of 0.44 and 0.63 and the cost of FRSULWAC ranges between 1070 and 3250 $/m^3$ with an average of 1793 $/m^3$, which is 15 times more expensive than NWC. This high cost is due to the high cost of the engineered LWA and reinforcing fibers. The mean and coefficient of variation of the compressive strength (f_c') were calculated and found to be 19.7 MPa and 0.08, respectively. For design purposes, it is more convenient to use f_c' equals 20 MPa with a bias factor of 0.99. The observed probability and probability density function (PDF) of normal distribution is shown in Fig. 3 with Chi-square goodness of fit χ^2 = 0.89. A larger database of experimental results would allow greater refinement of the results found in this study.

IV. Calculations and Results

IV.1. Modulus of Elasticity (MoE)

The formula given in the ACI 318-19 $E_c = 0.043\,\gamma_c^{1.5}\sqrt{f_c'}$, can be used to determine the modulus of elasticity (MoE = E_c) of plain concrete, when the dry density (γ_c) is between 1440 and 2480 kg/m^3 and the compressive strength is between 21 and 35 MPa. NWC has a higher MoE than ULWAC, because the elastic moduli of sand, stone, and gravel are greater than the elastic moduli of LWA. Low MoE associated with ULWAC makes it susceptible to excessive deflection. Adding synthetic short fibers does not influence the MoE significantly. The most important factor for the effect of fibers on the MoE of LWAC is the bond interface between the LWA and the cement matrix [24].

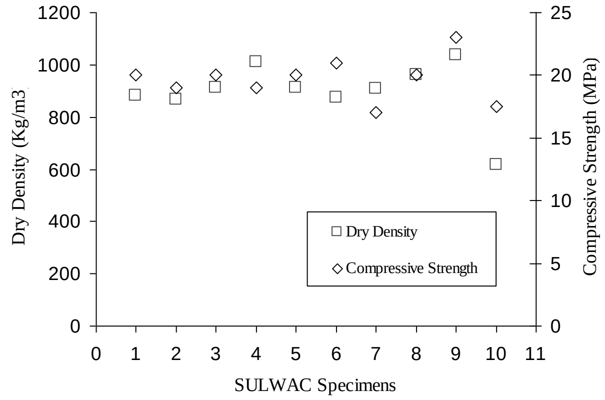

Fig. 2. Dry density and cylinder compressive strength of FRSULWAC mixes.

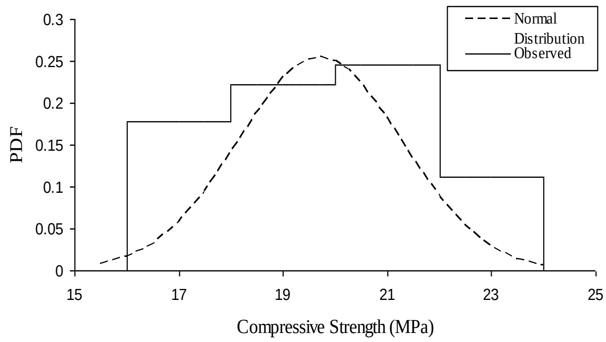

Fig. 3. Observed probability of FRSULWAC compressive strength vs. PDF of normal distribution.

To accurately determine the MoE of FRULWAC, 11 data points collected from 8 design papers (listed in Appendix A and labeled with letter E) with mix proportions and engineering mechanical properties summarized in Table I, were used. The experimentally collected data showed an average increase of 13% relative to the standard ACI-318 formula, when V_f is between 1.4 and 1.9%. A similar observation was reported for SLWC reinforced with synthetic short fibers [25], when it was found that the ACI formula failed to predict the MoE, and tried to underestimate the experimentally measured values. However, the ACI equation is still appropriate since the real values may deviate from this formula by up to 20% [4].

A relationship between Ω and V_f was constructed as shown in Fig. 4. The term Ω represents the ratio of the experimentally measured MoE to the theoretical values calculated using the ACI equation. A slight increase in the MoE with the addition of fiber was observed, when $V_f \geq 1.6\%$. A simple line was used to fit the data points. However, a conservative and slightly modified equation, to predict the MoE (MPa) of FRULWAC that could increase the accuracy of the current ACI formula, was obtained by multiplying the experimentally collected data points by 0.95 followed by line fitting (Eq. 1).

$$E_c = 0.028\, V_f\ \gamma_c^{1.5} \sqrt{f_c'} \tag{1}$$

where:

V_f : % fiber content by volume fraction,

γ_c : density of ULWAC in Kg/m^3,

f_c' : cylinder compressive strength in MPa.

TABLE I

MIX PROPORTIONS AND MECHANICAL PROPERTIES OF ULWAC USED TO CALCULATE MOE AND MOR.

Proportions	Range	Mechanical properties	Range
% cementitious materials (*cm*) ratio by weight	0.39-0.462	f_c' (MPa)	12.3-21
% LWA by volume	0.544-0.65	Dry density (Kg/m^3)	597-940
Cement-to-*cm* ratio by weight	0.4-0.5	Modulus of elasticity (GPa)	2.9-5.0
% fibers by volume	1.16-1.9	Modulus of rupture (MPa)	1.6-4.7
w/cm (water-to-*cm* ratio)	0.41-0.78	Slump (mm)	5.0-100.0

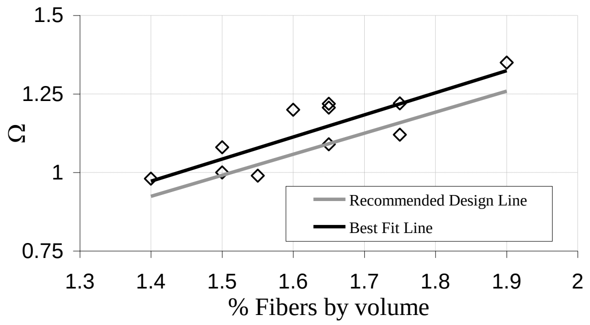

Fig. 4. Relationship between V_f and Ω.

IV.2. *Modulus of Rupture* (MoR)

The theoretical modulus of rupture (MoR) of plain NWC and SLWAC can be calculated using the equation given in ACI 318-19 $f_r = 0.7\lambda\sqrt{f_c'}$, where λ is the aggregate factor and equals 0.75 for all-lightweight aggregate. Adding synthetic short fiber increases the MoR significantly, and good dispersion with high V_f plays an important role. Tests on ULWAC reinforced with polyethylene fibers have shown an increase in MoR of 80.3%, 223.3%, and 325.6%, compared to plain ULWAC, when V_f = 0.5%, 1.0% and 1.5%, respectively [7]. An increase of 48% in splitting tensile strength was reported with the addition of 0.4% by weight PVA fiber to ULWAC [26].

To accurately determine the MoR of FRULWAC, 20 data points collected from 13 design papers (listed in Appendix A and labeled with letter R) with mix proportions and engineering mechanical properties summarized in Table I were used. A relationship between $\Psi = \dfrac{10^3\, f_r^*}{\gamma_c^2\, f_r}$ and V_f was constructed, as shown in Fig. 5, where f_r^* is the experimental MoR, f_r is the theoretical MoR, and γ_c is the dry density of ULWAC (Kg/m^3). The average ratio of the experimentally collected data to the ACI equation values (theoretical) was 1.28. A very good correlation between Ψ and V_f can be recognized, and a simple line was used to fit the data points. However, a simplified and conservative second order equation, to estimate the MoR of FRULWAC that could substitute the current ACI formula, was obtained by multiplying the experimentally collected data points by 0.95 followed by curve fitting (Eq. 2). The aggregate factor (λ) of 0.75 is implicitly incorporated into the equation.

$$f_r = 0.5 \times 10^{-6}\, V_f^2\ \gamma_c^2 \sqrt{f_c'} \tag{2}$$

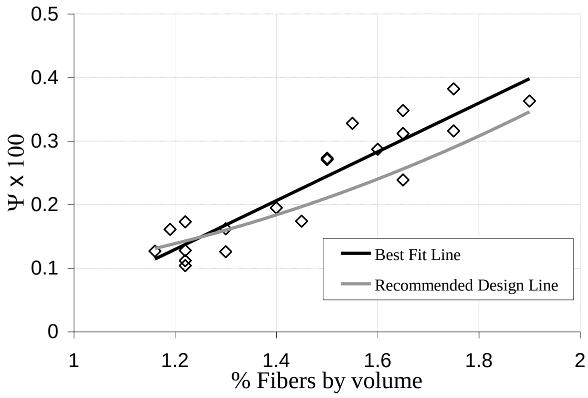

Fig. 5. Relationship between V_f and Ψ.

IV.3. *Ductility*

Ductility is defined as the ability of the material to absorb the inelastic energy without losing the loading capacity. Therefore, higher inelastic energy absorption may ensure higher ductility. Energy-based method can be utilized to compute the ductility index (μ_E) using the following equation [27]:

$$\mu_E = \frac{1}{2}\left(\frac{E_t}{E_e} + 1\right) \tag{3}$$

where:

E_t – total energy computed as the area under the load deflection curve,

E_e – elastic energy computed as the area beneath line S, which represents the elastic slope to quantify the elastic energy, up to the point of intersection with $P_{failure}$ as shown in Fig. 6.

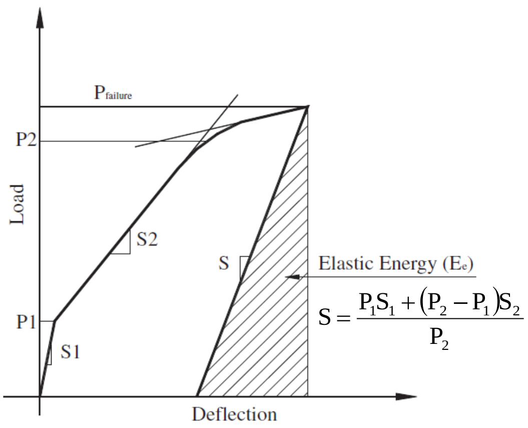

Fig. 6. Definition of energy-based ductility index.

Remarkably improved load-deflection curves, under three-point loading test, of high-performance SLWAC and SULWAC plates were experienced, when PVA shorts fibers of length 15 mm were added to the concrete composites with V_f of 1.5% [16]. The plates have width, thickness, and length in the ratio of 5.85:1:23.5. Impressive load-deflection curves, under third-point loading test, of high-performance SULWAC beams were observed [Appendix A-11]. The concrete composites were reinforced with 1.9% volume fraction of PVA short fibers of length 6.35 mm. The beams have width, thickness, and length in the ratio of 1:1:3.5. In this study, the ductility indices for these plates and beams were evaluated from the load-deflection curves up to the maximum applied load, as shown in Figs. 7 and 8, using Eq. 3. It was found that the ductility indices for plates were in the range of 6.5 and 10.5 with an average value of 8, while the ductility indices for beams were 4.4, 6.5 and 8.3 with an average value of 6.4. It can be seen that the ductility indices of all plates and beams are above the minimum required value of 3.0 [28].

IV.4. Stress-Strain Behavior

The prediction of accurate stress–strain behavior of concrete is of great importance to properly design reinforced concrete structural members. ACI 318-19 specifies the ultimate compressive strain (ε_{cu}) as 0.003 for beams, slabs and columns. The strain corresponding to the peak stress (ε_0) for plain NWC and lightweight concrete (LWC) is usually between 0.002 and 0.003.

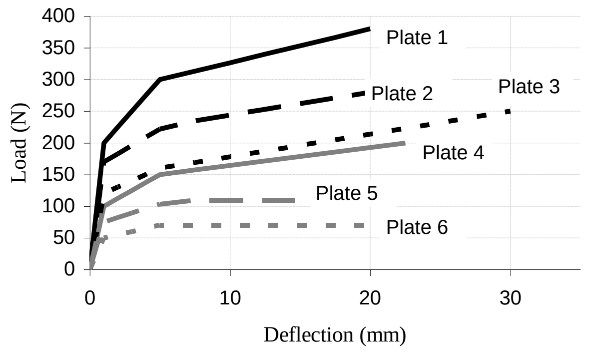

Fig. 7. Load-deflection curves used to calculate μ_E of FRLWAC and FRULWAC plates.

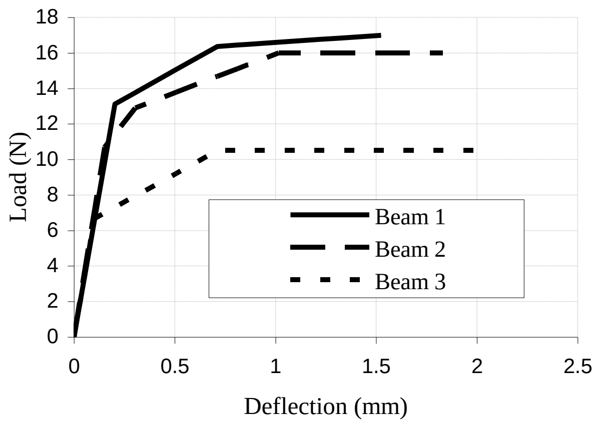

Fig. 8. Load-deflection curves used to calculate μ_E of FRSULWAC beams.

Adding randomly dispersed short synthetic fibers, in relatively large amounts, to the concrete mix will increase ε_{cu} considerably. The general behavior of the stress-strain curve of FRC can be divided into four stages: linear elastic ascending stage, nonlinear ascending stage, cracking and residual softening descending stages.

ε_0 between 0.0039 and 0.0044 and ε_{cu} of 0.022 were observed, when FRC and FRLWAC reinforced with 1.0% and 2.0% volume fraction of synthetic short fibers (PVA, Carbon and PP) were tested in axial compression [29] [30]. A lower value of ε_{cu} = 0.01 was observed, when PP added to LWAC with V_f = 0.4%, while ε_0 remained unchanged [31]. Fig. 9 shows 14 normalized stress-strain curves taken from the three studies mentioned above.

An analytical model to predict the stress-strain behavior, under axial compression, is proposed based on the average of the corresponding values of the collected data with ε_0 and ε_{cu} of 0.004 and 0.012, respectively. The new model consists of four linear stages. The first ascending stage extends up to $0.6f_c'$ with corresponding strain of 0.002, while the second ascending stage extends

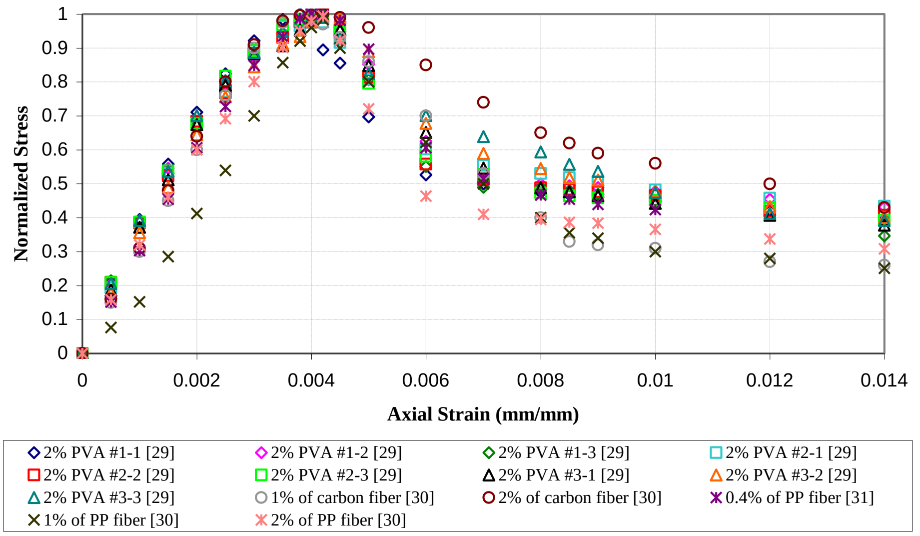

Fig. 9. Normalized stress-strain curves for different FRC composites.

up to peak stress f'_c with corresponding strain of ε_0. The first descending stage, cracking stage, drops from f'_c to $0.6 f'_c$ with corresponding strain of 0.006, while the second descending stage, residual softening stage, drops from $0.6 f'_c$ to $0.4 f'_c$ with corresponding strain of ε_{cu}. These 4 stages can be expressed mathematically as follows:

$$f_c = 300\,\varepsilon\, f'_c \quad \text{when} \quad 0 \le \varepsilon \le 0.002 \qquad (4a)$$

$$f_c = (0.2 + 200\varepsilon) f'_c \quad \text{when} \quad 0.002 \le \varepsilon \le 0.004 \qquad (4b)$$

$$f_c = (1.8 - 200\varepsilon) f'_c \quad \text{when} \quad 0.004 \le \varepsilon \le 0.006 \qquad (4c)$$

$$f_c = (0.8 - 33.34\varepsilon) f'_c \quad \text{when} \quad 0.006 \le \varepsilon \le \varepsilon_{cu} \qquad (4d)$$

The term $f_c = 300 f'_c$ has a very close value to the MoE calculated using Eq. 1. This new model is shown in Fig. 10, and is recommended for concrete reinforced with synthetic short fibers when V_f ranges between 1 and 2%.

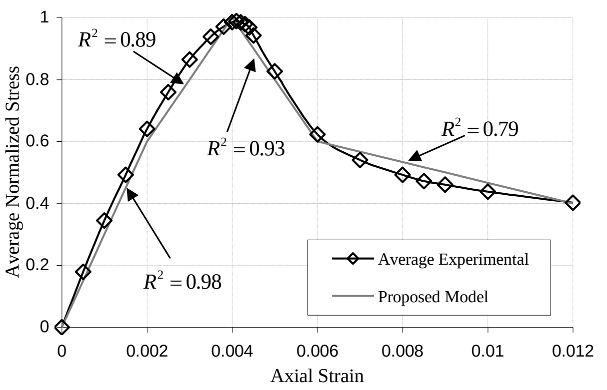

Fig. 10. Normalized average experimental stress-strain curve and the proposed model.

V. Conclusions

The following conclusions can be drawn from this study:

1. The production of SULWAC that has the capability to exhibit strain-hardening prior to failure is associated with high initial cost, which can be considered a major disadvantage (15 times more expensive than NWC).
2. The reinforcement of ULWAC by synthetic short fibers is not a suitable solution to enhance the MoE. However, a significant increase in the MoR was noticed, especially at high fiber content levels, compared to the values obtained using the current ACI equation.
3. A slightly modified equation was proposed to predict the MoE of FRULWAC that accounts for the volume fraction of short fiber. The new equation could increase the accuracy of the current ACI equation.
4. A new equation was proposed to predict the MoR of FRULWAC that accounts for the dry density of the concrete mix, and the volume fraction of short fiber. The new equation could substitute the current ACI equation.
5. Adding fiber in high volume fraction (between 1.5 and 1.9%) was proved to be an effective way to enhance the ductility of ULWAC composites, and the beneficial effect of synthetic fibers is pronounced. Energy-based equation and load-deflection curve were used to calculate the ductility index. Ductility indices for beams and plates were above the minimum requirement of 3.0.
6. A new analytical model that consists of four linear stages was proposed to describe the stress-strain response of fiber reinforced concrete composites

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under axial compression with ε_0 and ε_{cu} of 0.004 and 0.012, respectively.

7. An innovative design concept of corrosion-free reinforced concrete structural members can be utilized using a hybrid system of FRSULWAC that has the capability to exhibit noticeable strain hardening behavior prior to failure reinforced with fiber reinforced polymer (FRP) bars. The lack of ductility in FRP bars can be compensated by the ductile response of FRSULWAC. However, further investigations and studies are needed to adopt this design concept.

Appendix A: Design Papers Used in this Study

1. California Polytechnic State University, San Luis Obispo Canoe Team, Jumanji NCCC Design Paper. California Polytechnic State University, San Luis Obispo, CA, USA, 2015.[S]
2. McGill University Canoe Team, Anakalypse NCCC Design Paper. McGill University, Montreal, QC, Canada, 2014.[R]
3. University of California, Los Angeles Canoe Team, Arcturus NCCC Design Paper. University of California, Los Angeles, CA, USA, 2015.[S,R]
4. University of California, Los Angeles Canoe Team, Imperia NCCC Design Paper. University of California, Los Angeles, CA, USA, 2014.[S,R]
5. University of California, Los Angeles Canoe Team, Meridian NCCC Design Paper. University of California, Los Angeles, CA, USA, 2013.[S,R]
6. University of California, Los Angeles Canoe Team, Hakuna Matata NCCC Design Paper. University of California, Los Angeles, CA, USA 2012.[S,R]
7. University of California, Los Angeles Canoe Team, Rock the Boat NCCC Design Paper. University of California, Los Angeles, CA, 2010.[S]
8. University Laval Concrete Canoe Team, LCC-22 NCCC Design Paper. University Laval, Québec, QC, Canada, 2017.[E,R]
9. University Laval Concrete Canoe Team, Space Oddity NCCC Design Paper. University Laval, Québec, QC, Canada, 2016.[E,R]
10. University Laval Concrete Canoe Team, Bluenose NCCC Design Paper. University Laval, Québec, QC, Canada, 2015.[E, R]
11. University Laval Concrete Canoe Team, Maximus NCCC Design Paper. University Laval, Québec, QC, Canada, 2014.[S,E,R]
12. University Laval Concrete Canoe Team, Ephemere NCCC Design Paper. University Laval, Québec, QC Canada, 2013.[E,R]
13. University Laval Concrete Canoe Team, Borealis NCCC Design Paper. University Laval, Québec, QC, Canada, 2012.[E,R]
14. University Laval Concrete Canoe Team, Voltage NCCC Design Paper. University Laval, Québec, QC, Canada, 2011.[E, R]
15. University Laval Concrete Canoe Team, Norseman NCCC Design Paper. University Laval, Québec, QC, Canada, 2010.[E,R]

Appendix B

TABLE B-I
MECHANICAL PROPERTIES OF FRSULWAC.

Specimen	Compressive Strength (MPa)	Dry Density (Kg/m^3)	Slump (mm)	% Air Content	w/*cm*	% V_f	% aggregate by weight	% *cm* by weight
SULWAC 1	20	881	44	7.64	0.28	1.3	0.319	0.519
SULWAC 2	19	865	44	10.83	0.28	1.45	0.32	0.516
SULWAC 3	20	913	44	3.88	0.28	1.3	0.319	0.519
SULWAC 4	19	1009	44	12.65	0.28	1.45	0.28	0.55
SULWAC 5	20	913	51	10.7	0.43	1.22	0.295	0.48
SULWAC 6	21	873	51	6.94	0.47	1.2	0.26	0.492
SULWAC 7	17	910	51	1.83	0.45	1.22	0.263	0.498
SULWAC 8	20	960	76	14.9	0.377	0.25	0.3	0.478
SULWAC 9	23	1038	76	2.5	0.377	0.25	0.293	0.484
SULWAC 10	17.5	617	25	2.75	0.68	1.9	0.2	0.46

TABLE B-II:
ULTRA-FINE AND FINE AGGREGATE PROPORTIONS BY WEIGHT OF FRSULWAC.

Aggregate: Saturated surface dry (SSD)	SULWAC 1	SULWAC 2	SULWAC 3	SULWAC 4	SULWAC 5	SULWAC 6	SULWAC 7	SULWAC 8	SULWAC 9	SULWAC 10
3M™ K15 (0.177 mm)	0.116	0.119	0.116	0.082	0.116	0.135	0.135	-	-	0.42
3M™ K37 (0.045 mm)	-	-	-	-	-	-	-	-	-	0.27
3M™ S38 (0.105 mm)	-	-	-	-	-	-	-	0.041	0.027	-
Poraver® 0.04-0.25 mm	-	-	-	-	-	-	-	0.11	0.027	-
Poraver® 0.1-0.3 mm	0.209	0.208	0.209	0.096	0.209	0.243	0.189	0.329	0.122	0.31
Poraver® 0.25-0.5 mm	0.209	0.208	0.209	0.274	0.209	0.243	0.243	0.507	0.419	-
Poraver® 0.5-1.0 mm	0.209	0.208	0.209	0.274	0.209	0.243	0.243	-	0.257	-
Poraver® 1-2 mm	-	-	-	-	-	0.135	0.189	-	0.122	-
Crushed Glass 0.1-2.0 mm	0.257	0.257	0.257	-	-	-	-	-	-	-
Crushed Concrete 0.1-2.0 mm.	-	-	-	-	0.255	-	-	-	-	-
Pelletized Slag < 4.75 mm	-	-	-	0.274	-	-	-	-	-	-
Q-Cel® 6014 0.005-0.2 mm	-	-	-	-	-	-	-	0.014	0.027	-

TABLE B-III
CEMENTITIOUS MATERIALS PROPORTIONS BY WEIGHT OF FRSULWAC.

Cementitious Materials (*cm*)	SULWAC 1	SULWAC 2	SULWAC 3	SULWAC 4	SULWAC 5	SULWAC 6	SULWAC 7	SULWAC 8	SULWAC 9	SULWAC 10
Portland Cement Type I	0.4	0.4	0.4	0.45	0.4	0.4	0.4	0.35	0.35	0.5
Slag	0.2	0.2	0.2	0.18	0.2	0.2	0.2	0.5	0.5	-
Pozzolan (VCAS)	0.4	0.4	0.4	0.35	0.4	0.4	0.4	0.1	0.1	-
Hydrated Lime Type S	-	-	-	-	-	-	-	0.05	0.05	-
Waterproofing (Xypex)	-	-	-	0.02	-	-	-	-	-	-
Silica Fume	-	-	-	-	-	-	-	-	-	0.22
Fly Ash Type F	-	-	-	-	-	-	-	-	-	0.28

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