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FLEXURAL BEHAVIOR OF REINFORCED LIGHTWEIGHT FOAMED CONCRETE BEAMS USING GFRP BARS

A Thesis Submitted to Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering

By

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DEDICATION

To her love and patience and her support …..

My Mom

To my great honor and my idol ......

My Dad

To their support advice and encouragement …..

My Sisters & Brothers

To every heart beats with love and faith, To all who wish me benevolent….

my friends

Dhamyaa Ghalib Jassam

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ABSTRACT

The lightweight foamed concrete (LWFC) applications in the structural building are so restricted due to its low strength and brittleness. The experimental work of this study includes two parts: the first involves improving the mechanical properties for the LWFC using additives and fibers. Eleven mixes were cast and tested for compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity with target density 1800 kg/m^3. Two types of fibers were added to LWFC mix, which were steel fiber, and polypropylene fiber, and hybrid fibers (steel+ polypropylene). The test results showed that the fibers addition into the LWFC mix decreases the flowability and enhance the mechanical properties. The hybrid fibers mixed with (0.4%+ 0.2%) of (steel+ polypropylene) fibers gave the best results and used in casting the reinforced concrete beams.

The second part of this work is the experimental study of the behavior of reinforced (Lightweight foamed, Normal) concrete beams using Glass Fiber Reinforced Polymer (GFRP) bars as the main reinforcement under two point flexural loads. This part includes twelve beams with dimensions (200mm x 250 mm x 1500 mm), divided into two groups: six of lightweight foamed concrete and six of normal concrete beams. For each group: three beams reinforced with GFRP bars in three different reinforcement ratios, two beams reinforced with hybrid

(GFRP+steel) reinforcements, and one beam reinforced with steel bars for comparison

The main variables considered are the concrete type (Lightweight foamed concrete, Normal concrete), reinforcement type (GFRP bars, Steel bars), and GFRP reinforcement ratio. The main parameters considered in this stage of experimental work are the ultimate load capacity, deflection, cracks width, concrete strain, and main reinforcement strain at mid-span length. Therefore, the experimental serviceability limitation, load-deflection curve, load-main reinforcement strain curve, load-concrete strain curve, load-neutral axis depth, ductility index and deformability factor are prepared for all tested beam.

The service load is 35% of the ultimate load for each tested beams. At the service load, the stiffness of GFRP reinforced lightweight foamed concrete beams was less than that of the normal concrete beams, thus the deflection of LWFC beams was higher than the deflection of normal concrete beams. According to the ductility index, the deformability factor of lightweight foamed concrete beams is more than that of normal concrete beams.

The experimental test results of ultimate load, deflection and crack width for all tested beams were compared with that estimated by ACI 440.1R-06 and ACI 318M-14 models. The comparison showed a good agreement between the experimental and predicted results such as increasing the reinforcement ratio and increasing the steel ratio in the hybrid reinforcing GFRP/steel. The ratio of predicted results to the experimental results was (1.1) at service load.

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P	Applied load indicated by the testing machine in N
A_f	Area of tension FRP reinforcement
A_s	Area of tension steel reinforcement.
E_e	Area of the triangle formed below line S, up to the point of failure load
d_1	Average of four readings in flow test, in mm.
S	Bar spacing (center to center) in mm
L, l	Clear span length in mm
k_b	Coefficient related to bonding of FRP bars
I_{cr}	Cracked moment of inertia in GPa
M_{cr}	Cracking moment in kN.mm
f_{cu}	Cube compressive strength of concrete in MPa.
$f_c{}'$	Cylinder compressive strength of concrete in MPa.
$D_{0.001}$	Deflection at concrete strain 0.001
D_u	Deflection at ultimate for ductility index based on deformability
E_f	Design or guaranteed modulus of elasticity of FRP defined as mean modulus of sample of test specimens in MPa
f_{fu}	Design tensile strength of FRP
c_b	Distance from extreme compression fiber to neutral axis at balanced strain condition in mm
c	Distance from extreme compression fiber to the neutral axis
μ_E	Ductility Index Based on Energy Method
d	Effective depth in mm
I_f	Effective moment of inertia in MPa
P_{exp}	Experimental failure load

$P_{s,s}$	Experimental values for the service load for maximum concrete stresses
$P_{s,c}$	Experimental values for the service load for maximum permissible crack width
$P_{s,d}$	Experimental values for the service load for maximum permissible deflection
β_1	Factor relating depth of equivalent rectangular compressive stress block to neutral axis depth
n_f	FRP modulus ratio: FRP modulus of elasticity to concrete modulus
ρ_f	FRP reinforcement ratio
ρ_{fb}	FRP reinforcement ratio producing balanced strain conditions
I_g	Gross moment of inertia in MPa
h	Height of the rectangular cross section in mm
$P_{0.001}$	Load at concrete strain 0.001
P_u	Load at ultimate
ε_1	Longitudinal strain (ε_1) of (0.000050)
ε_2	Longitudinal strain produced by stress S_2
w_{max}	Maximum crack width in mm
M_a	Maximum moment in member at stage deflection is computed in kN.m
λ	Modification factor reflecting the reduced mechanical properties of lightweight concrete, which is (0.85) for sand-lightweight concrete.
E_c	Modulus of elasticity of concrete in MPa
E_s	Modulus of elasticity of steel in MPa
f_r	Modulus of rupture in MPa
N.A	Neutral axis depth in mm.
M_n	Nominal moment capacity in kN.m

d_2	Original inside base diameter in flow test, in mm.
k	Ratio of the neutral axis depth to reinforcement depth
β	Ratio of, distance between, neutral axis and tension face to distance between neutral axis and centroid of reinforcement
β_d	Reduction factor
a	Shear span in mm
f_{ct}	Splitting tensile strength for concrete in MPa
n_s	Steel modulus ratio: steel modulus of elasticity to concrete modulus
ρ_s	Steel Reinforcement ratio
ε_c	Strain in concrete
S_1	Stress corresponding to 40% of ultimate load
S_2	Stress corresponding to a longitudinal strain (ε_1) of (0.000050)
f_f	Stress in FRP reinforcement in tension in MPa
d_c	Thickness of cover from tension, face to center of closest bar mm
E_t	Total energy computed as the area under the load-deflection curve
Δ_u	Ultimate Deflection
ε_{cu}	Ultimate strain in concrete
w/c	Water to cement ratio
b	Width of rectangular cross section in mm

List of Abbreviations

Abbreviations	Descriptions
ACI-318-14	American Concrete Institute: Building Code Requirements for Structural Concrete and Commentary
ACI 440.1R-06	American Concrete Institute: Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars
AFRP	Aramid Fiber Reinforced Polymer
FB	Base Foamed Concrete mix
BS	British Standards
CAN/CSA-S806-12	Canadian Standards Association: Design and Construction of Building Structures with Fiber-reinforced Polymers
CFRP	Carbon Fiber Reinforced Polymer
P_{exp}	Experimental load of tested beams
FRP	Fiber Reinforced Polymer
FSTP1	Foamed Concrete mix with (0.2% Steel fiber+0.2% Polypropylene fiber)
FSTP2	Foamed Concrete mix with (0.2% Steel fiber+0.4% (Polypropylene fiber
FPP1	Foamed Concrete mix with (0.2%) Polypropylene fiber
FST1	Foamed Concrete mix with (0.2%) Steel fiber
FPP2	Foamed Concrete mix with (0.4%) Polypropylene fiber
FST2	Foamed Concrete mix with (0.4%) Steel fiber
FSP5	Foamed Concrete mix with (0.5%) Superplasticizer
FSP8	Foamed Concrete mix with (0.8%) Superplasticizer
FSF10	Foamed Concrete mix with (10%) Silica Fume
FSF5	Foamed Concrete mix with (5%) Silica Fume
GFRP	Glass Fiber Reinforced Polymer
I.Q.S	Iraqi Central Organization for Standardization and Quality Control
LWFC	Lightweight Foamed Concrete
$P_{s,d}$	Service load of beam at which the deflection equal to $L/240$
$P_{s,c}$	Service load of beam at which the maximum crack width equal to 0.7mm
$P_{s,s}$	Service load of beam that corresponding to 0.6 of the ultimate compressive strength of concrete.
SLS	Serviceability Limit State

Chapter One
Introduction

1. General Remarks

1.1 Lightweight Foamed Concrete

According to ASTM C330/C330M which uses density to classify lightweight concrete into three categories depending on its application. These categories include non-structural concrete with a low-density (300 to 800 kg/m^3) used for thermal insulation. Secondly, structural lightweight concrete with a density (1120 to 1920 kg/m^3) with the compressive strength above 17.0 MPa and used for structural applications, and concrete with moderate strength placed between the above two classes with a compressive strength (7.0 MPa to 17.0 MPa) (ASTM C330\C330M, 2009).

Lightweight foamed concrete is considered as type of concrete which can be described as a mix of cement, sand, water and enter the air into it which leads to increasing the mixture volume and reduces its weight.

According to ACI 523.2R-96 the material, which is commonly referred to as cellular or aerated concrete, is defined as:

"A lightweight product consists of Portland cement and/or lime with siliceous fine material, such as sand, slag, or fly ash, mixed with water to form a paste that has a homogenous void or cell structure. The cellular structure is attained essentially by inclusion of macroscopic voids resulting from a gas releasing chemical reaction or the mechanical incorporation of air or other gases (autoclave curing is usually employed)" (ACI Committee 523.2R, 1996).

Thus, the foamed concrete defined as a highly aerated mortar with an air content higher than (20%) by volume of the mixed mortar which entered foam (Brady et al., 2001).

The aim of sustainable construction is to decrease the environmental effects on a structural building along its lifetime and optimizing its economic viability and the safety and comfort for its residents. The sustainable construction principles are applied to the whole life period of the construction, during the designing, construction and operation process of building projects.

Lightweight foamed concrete has feature properties that make it as a sustainable construction material by reducing resourcing consumption and using recyclable resources where its production consists of the recycled material such as fly ash and silica fume. Also, the low in self-weight of foamed concrete contributes to reducing the reinforcement, member size, and saving in transportation and handling.

1.1.1 Applications of Lightweight Foamed Concrete

The use of lightweight foamed concrete in the construction of building reduces the reinforcements, member cross-sections, and foundations size. Foamed concrete is distinguished by significant properties such as low in self-weight, self-leveling, thermal and sound isolation, and fire resistance, thus it has exceptional application for different objectives. The foamed concrete applications have become common in the worldwide, especially in the adverse weather regions, earthquakes, and storms.

In 2011, lightweight foamed concrete was used for filling in walls along the west edge to accommodate additional lanes adjacent to big Sioux and Missouri River on the west and railroad to accommodate additional lanes.

Plate (1-1): Application of lightweight foamed concrete fill in Sioux city, Iowa.

In the south of Iraq, lightweight foamed concrete is used in the roof as a layer of leveling over the roof slab directly because of its lightweight instead of using dirt. Also it is used in the floors under the tiles where it is casting at one level without any differences in the level and then set the finishing material of marble or porcelain with an adhesive material as seen in the plate (1-2).

Plate (1-2): The use of LWFC in Al Hussain Quran School in Karbala city, Iraq, 2017.

1.1.2 Characteristics of Foam Concrete

1. **Lightweight:** It is light weight in comparsion with the normal concrete with a dry density of (300.0 kg/m^3 to 1900.0 kg/m^3) that decreases the dead load of the structure.
2. **Flowability:** The flowability of foamed concrete is defined as self-compaction concrete with no need for vibration, and free flowing.
3. **Workability:** foamed concrete has a high workability that makes it desired dimension including angles and any shapes.
4. **Thermal and Sound Insulation:** because of the air voids in foamed concrete, which dampen heat and sound transfer.
5. **Fire resistance:** Lightweight foamed concrete supply approximately twice the fire resistance of the normal concrete.
6. **Sustainable material**: Low aggregate usage (reduce resource consumption), and foam concrete production consists of the waste material such as fly ash and silica fume.
7. **Reducing the damages of the earthquake risk:** The earthquake loads influencing the structures are proportional to the mass of those structures.

Many studies focus on enhance lightweight foamed concrete durability and mechanical properties with various types of additions and replacements. Lightweight foamed concrete is a very brittle anisotropic material with high strength to weight ratio. The inclusion of steel fibers into LWFC is one approach to enhance its mechanical properties.

The adding of silica fume to the foamed concrete improves the its mechanical properties by filling the area between cement granules that leads to increase the density and the strength of the foamed concrete mixture and also to improve the bonds between cement and aggregate due to the pozzolanic action of the silica fume which leads to improve the bond between the aggregate and concrete matrix to give a better overlap between the aggregates and the cement paste.

Lightweight foamed concrete has a low self-weight compared with normal concrete. This leads to reducing the dead load in the construction building and a smaller loads of column which directly leads to reducing the applied loads on the foundation, and this contributes to the reduction in all cost of building. Lightweight foamed concrete has a high strength to weight ratios which also contributes to having longer spanning of beams and also using a lesser number of the intermediate column which that leads the possibility of opening up more free spaces (Brady et al., 2001).

1.2 Fiber Reinforced Polymer Bars (FRP)

In the steel reinforced concrete structure, the steel bars corrosion is the most significant problem. To avoid this problem, the use of fiber reinforced polymer (FRP) bars instead of traditional steel bars presents a very effective solution. The corrosion process ultimately causes concrete deterioration and loss of serviceability (Maranan et al., 2015).

"Fiber reinforced polymer (FRP) bars are composite materials made of fibers embedded in a polymeric resin such as glass, aramid and carbon. FRP bars have an alternative properties such as being light in weight, noncorrosive, and nonmagnetic (thermally and electrically non-conductive) material, and high tensile strength, that make them suitable for use as structural reinforcement" (ACI Committee 440.1R, 2006).

1.2.1 The Properties of Fiber Reinforced Polymer (FRP):

The FRP composites have many advantages over conventional steel reinforcement (ACI Committee 440.1R, 2006), in terms of:

1. **Lightweight material:** FRP bars have a low weight comparing with the conventional steel bars that contribute to reducing the dead load that increases the live load capacity.
2. **Good durability:** FRP bars have a great resistance to salts and other chemicals materials which prevent the corrosion of reinforcement, concrete cracking, and spalling related in the steel reinforced concrete**.**
3. **Long service life:** the construction reinforced with FRP bars have a perfect performed in severe conditions for many years with a low maintenance.
4. **Easy installation:** FRP reinforcement is fast in proceeding due to its low weight, no need for welding, and easy in the handling.
5. **Fatigue and impact resistance:** FRP bars have high fatigue duration and impact resistance.

The FRP reinforcement advantages and disadvantages of for concrete structures listed in Table (1-1), as compared with conventional steel reinforcement (ACI Committee 440.1R, 2006).

Table (1-1) Advantages and disadvantages of FRP reinforcement

FRP Reinforcement Advantages	FRP Reinforcement Disadvantages
Height tensile strength	No yield before failure.
Height Resistant to Corrosion	Low transfer strength
Non magnetic	Low modulus of elasticity.
Low weight (about 1/3 to ¼ of steel weight)	Susceptibility of damage to polymeric resins and fibers under ultraviolet radiation exposure
High fatigue resistant	Low durability of some glass and aramid fibers in an alkaline environment
Low electric and thermal conductivity	High coefficient of thermal expansion of fibers relative to concrete. Maybe responsive to fire depending on the type and thickness of concrete cover

1.2.2 History and Use of FRP Bars

The properties of FRP reinforcement must be considered when deciding whether or not the FRP reinforcement is proper or important in a specific structure.

In the middle of the 1990s, the most applications of FRP reinforcement were in Japan with more than 100 trade projects (ACI Committee 440.1R, 2006).

During the 1970s, the use of FRP reinforcement in the construction of bridges to prevent the deterioration due to corrosion in the U.S. has become apparent. (ACI Committee 440.1R, 2006).

In 1986, the FRP reinforcements were first used in Germany with the construction of pre-stressed FRP Highway Bridge. (ACI Committee 440.1R, 2006).

In 1996, the first completely footbridge reinforced with FRP project was installed in the EUROCRETE in the United Kingdom as seen in the plate (1-3) below (CEB-fib, 2007).

In 1997, GFRP bars were used in the Crowchild Bridge deck construction in Canada (ACI Committee 440.1R, 2006).

In (2016), GFRP bars were used in China in the construction of sea walls in Yancheng city and underwater tunnel of Weisan road as seen in the plate (1-4) and (1-5).

Plate (1-3): The first concrete footbridge in Europe reinforced with only FRP bars (ACI committee 440.1R, 2006).

Plate (1-4) The use of GFRP in the sea walls in Yancheng city, China, 2016

Plate (1-5) GFRP use in the underwater tunnel of Weisan road in Nanjing,China, 2016.

1.2.3 FRP Characteristics:

FRP bar is anisotropic material and can be manufactured using a different techniques such as braiding, and weaving. The properties of FRP bar depend on many factors such as the volume of fiber, type of fiber, resin type, fiber adjustment, dimensional effects, and quality control during manufacturing (ACI Committee 440.1R, 2006).Table (1-2) shows the physical and mechanical properties GFRP and steel bars.

Table (1-2): The Characteristics of GFRP bars and Steel bars.

Characteristics		GFRP	Steel
Specific Weight		1.25 to 2.1	7.9
Nominal Stress of Yield (MPa)		N/A	276 to 517
Tensile strength (MPa)		483.0 to 1600.0	482 to 692
Elastic modulus, $\times 10^3$ GPa		35 to 51.0	200
Strain of Yield, %		N/A	0.145 to 0.253
Strain of Rupture, %		1.2 to 3.1	6.0 to 12.0
Coefficients of Thermal Expansion $\times 10^{-6}$/°C	Longitudinal, α_L	6.0 to 10.0	11.7
	Transverse, α_T	21.0 to 23.0	11.7

1.3 Research Significance

In the concrete structures, a high percent of the overall weight of structure comes from the concrete self-weight. Thus the reducing its density leads to a significant benefit. The use of lightweight concrete in the concrete structure is one of the most efficient ways to reduce the dead weight of the structure. The use of lightweight foamed concrete in the structure leads to reduce the beams, columns and foundation size, because it reduces the dead weight. This leads to the reduction in the overall cost. Also, the good thermal insulation of the lightweight foamed concrete contributes to the reduction of the operating costs such as heating and air-conditioning.

The lightweight foamed concrete features a good thermal and sound insulation. Therefore, its use in construction provides a comfortable and convenient condition inside the building, which reduces the consumption of energy sources in heating and cooling.

The use of lightweight concrete is considered appropriate for the seismic design of the building. The lateral forces of the earthquake on the building structure is directly proportional to the weight of the structure, so the use of lightweight foamed concrete in construction structure will reduce the dead weight, and therefore the earthquake effect on the building will be less.

The FRP bars have a lighter weight compared with steel bars which reduces the cost of transportation including the easy of handling the bars in site.

Few studies were found at the local universities and around the world about the use of lightweight foamed concrete beams.

The ACI guidelines for the design and construction of FRP bars reinforced concrete, ACI440.1R-06, stated that the flexural and shear theories were developed for normal concrete. This study aims to investigate the flexural behavior at serviceability and ultimate limit state of GFRP bars of lightweight foamed concrete (ACI Committee 440.1R, 2006).

The FRP bars are a significant importance in the structures where non-metallic properties reinforcements are required like in the surroundings of some medical devices.

Also, the FRP bars is important in the constructions where the high ratio of weight to strength is required.

The use of steel fiber and polypropylene fiber in lightweight foamed concrete beams reinforced with FRP may present an effective solution to overcome the problem of ductility in the construction reinforced with FRP bars.

The FRP bars can be a sufficient alternative to the traditional steel reinforced concrete structure in corrosive environments or when the electromagnetic effects fields may be attended (Barris et al. , 2013).

The FRP reinforcement is a non-conductive material, thereby the demand increased for it to use in the construction of medical. Other FRP bars uses are improved due to the fact that non-corrosive advantages became best accepted and desired, specifically in constructions of the seawall, reactor bases, runways of the airport, and electronics laboratories (ACI Committee 440.1R, 2006).

1.4 Research Objectives

The main objective of this research is to investigate the flexural behavior of lightweight foamed concrete beams reinforced with GFRP bars. The study objectives can be stated in two parts:

Part One: Trail Mixes

Many experimental trial mixes of lightweight foamed concrete were casted and tested. The additives and two types of fibers (Steel fiber and polypropylene fiber) were used in these foamed concrete mixes in order to:

1. Investigate the effect of these additives and fibers on the mechanical properties of (LWFC) including, compressive strength, tensile splitting strength, flexural strength, and modulus of elasticity.
2. Producing lightweight foamed concrete suitable for structural applications and then choose appropriate mix for use in casting the beams.

Part Two: Reinforced Concrete Beams

1. Investigating flexural behavior of lightweight foamed reinforced concrete beams. Testing all beams under flexural load until failure in order to examine failure modes, deflection, cracks patterns, cracks width, concrete strain and main reinforcement strain that can help to correctly understand the overall behavior of beams under the serviceability requirements.
2. Experimentally testing the two types of concrete beams, lightweight foamed concrete and normal concrete, reinforced with different reinforcement ratios of GFRP bars as a main reinforcement. Comparing

the results to show the difference in the flexural behavior between the lightweight foamed concrete and normal concrete.

3. Studying and analyzing the results to decide the feasibility of using light weight foamed concrete as structural material and GFRP bars as main reinforcement in concrete structures.
4. Studying the serviceability limit state SLS and ductility of GFRP reinforced concrete beams.
5. Comparing the experimental deflection and cracks width with the predicted results estimated by equations of ACI-440.1R code.

1.6 Outline of the Thesis

Chapter One: Gives an introduction to the thesis. The chapter starts with the description for lightweight foamed concrete and its properties. Also, this chapter describes the GFRP properties and its applications with significance, objectives and scope of this research.

Chapter Two: contains a summarized review of relevant literature on the properties lightweight foamed concrete and reviews on the using of the FRP reinforcements in the field of constructions and researches in the field of the concrete beams reinforced with GFRP bars.

Chapter Three: at first details with the properties of the materials used and introduces the details of the experimental program. Design the mixes with or without admixtures, additives and fibers and conducting tests for the mechanical properties of all mixes such as compressive strength, tensile splitting strength, flexural strength and modulus of elasticity. Also instrumentation used in the tests are detailed.

Chapter Four: the experimental results are displayed, analyzed and discussed. The failure mode and the cracking patterns are commented on and the deflection behavior is discussed. Strains in the concrete and in the reinforcement are shown. The serviceability limit state SLS issues were studied.

Chapter Five: provides the conclusions drawn from this study, recommendations and suggestions for further studies.