Steel Fiber Addition in Eco-Friendly Zero-Cement Concrete: Proportions and Properties

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Abstract-The main objective of this paper is to study the behavior of eco-friendly zero-cement concrete, its proportions, and its properties. The experimental program involves casting and testing many specimens divided into three main groups according to the percentage of added steel fibers in order to investigate the effect of steel fibers on the density, compressive strength, modulus of elasticity, and splitting tensile strength of concrete. The experimental outcomes indicated that the percentage of steel fibers has a small impact on the dry density: adding 0.5% and 1% of steel fibers increased the dry density by about 0.9% and 1.6% respectively. The percentage of steel fibers has an important impact on the compressive strength: after 28 days, steel fibers increased the compressive strength by about 4.9% and 12.8% for added steel fiber percentages of 0.5% and 1%. Also, the results indicated that steel fiber had an important impact on the splitting tensile strength in concrete after 28 days of curing: adding 0.5% and 1% steel fibers increased the splitting tensile strength by about 11.8%and 23.2% respectively. Finally, adding steel fibers has an impact on the modulus of elasticity: after 28 days, adding 0.5% and 1% steel fibers improved the modulus of elasticity approximately by 1.7% and 5%.

Keywords-eco-friendly concrete; Pozzolime concrete; steel fibers; mechanical properties

I. INTRODUCTION

Global attention in eco-friendly and sustainable building materials has increased over the last decades and new constructional adhesives to replace conventional cement are researched. Researchers are being urged to investigate alternatives, such as the reinstitution of lime Pozzolanic systems. Lime might be considered an ecologically friendly binder due to its low energy needs, limited CO_2 emissions during production, and carbonation-induced CO_2 uptake through setting [1]. Lime natural Pozzolans are ancient building materials that were utilized in the process of building using masonry. The use of lime natural Pozzolanic materials had ceased to exist due to the development of inorganic bindings due to their sluggish setting and hardening. After the discovery of Portland cement in the nineteenth century, the use of natural pozzolan-lime binding materials decreased considerably. The environmental repercussions of the Portland cement production process have increased interest in lime-natural Pozzolan cement during the last 50 years [2]. Kadum [3], created Pozzolime, a unique, sustainable binder composed of hydrated-lime, silica fumes, and fly ashes. Many studies have shown that the addition of fibers, especially steel fibers, to concrete can reduce the requirement for conventional reinforcement in certain circumstances. Steel fibers increase the post-cracking tension response and cracking control qualities of reinforced concrete [4]. Utilizing deformed fibers, like those that are hooked, corrugated, or twisted, can further boost the mechanical strength of composite materials. Reportedly, deformed steel fibers give 3 to 7 times the fiber-matrix binding strength of straight fibers. Several factors, including fiber shape, fiber length, and curing conditions, influence the degree to which mechanical properties are enhanced [5]. Fibers are typically added to Fiber-Reinforced Cementitious Composites (FRCCs) in order to restrict the volumetric ratio of the mix to 3% in order to address mixing and casting issues such as fiber floating and balling.

Pozzolans are natural or man-made materials that are not cementitious on their own but, because they are made of aluminosilicates, they create hydraulic cement when mixed with lime hydrates. Authors in [6] investigated the viability of employing Pozzolans derived from natural sources in Algeria. This Pozzolanic material is seldom used in concrete, so its features have not been thoroughly examined. To learn more about the effectiveness of Pozzolan concrete, 6 concrete mixes were tested: one with Portland cement (as a reference), and 5

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with 10, 20, 30, 40, and 50% Pozzolan substitution of cement. To make lightweight aggregate concrete, shattered Pozzolan was used as the Lightweight Aggregates (LA), and fine sand was added to all mixes (LAC). Workability and density of fresh concrete mixes were evaluated. The compressive strength, splitting tensile strength, and flexural strength of hardened concrete samples were measured after 3, 7, 28, 90, and 365 days. All the concrete mixes had a constant cementitious material concentration of 400kg/m^3. The findings of this experiment indicated that the inclusion of Pozzolan at 20% of the weight of cement results in the greatest gain in strength among the evaluated mixes.

The experimental results of [7-12] showed that the addition of fly ash particles had little effect on the mechanical properties of normal concrete, while steel fibers had the greatest effect. The highest increase was reported in compressive and flexural strength.

II. EXPERIMENTAL WORK

A. Materials

1) Hydrated Lime

In Pozzolime concrete compositions, hydrated lime is utilized. The main component of hydrated lime is calcium hydroxide ($Ca(OH)_2$). The utilized hydrated lime was manufactured at a lime factory in Karbala and conforms to the Iraqi standard IQS No. 807 /2004 [13]. Table I displays the chemical analyses, chemical composition, and physical properties.

TABLE I. CHEMICAL AND PHYSICAL TEST VALUES OF HYDRATED LIME*

	Components	Results %	Limits IQS NO. 807
Chemical analysis	CaO + MgO	73.1	Min. 65%
	SiO_2	2.28	
	Al_2O_3	1.08	
	Fe_2O_3	0.23	
	MgO	0.46	5% Max.
	Fe_2O_3+Al_2O_3+ SiO_2	3.60	5% Max.
	SO_3	0.2	
	Loss on ignition	22.8	
	$Ca(OH)_2$	92.49	85% Min
	CaO % activity	70.12	
Physical test	CO_2 %	2.27	5% Max.
	Residue on 90µm	2.2	10% Max.
	Slaking time	24	Min
	Fineness m^2/kg	361	

* The tests were carried out in Karbala plant for cement and lime

2) Cement

This study utilized Portland cement, since it is readily accessible on the market. The used cement was utilized in the production of earlier concrete mixtures. The chemical and physical characteristics agree to the limitations of Iraqi standard No.5/1984 type V [14] (see Tables II and III).

3) Fine Aggregates

Local fine sand complying to zone two of the IQS No. 45 was utilized as FA [15]. According to the findings, the FA satisfies the grading requirements of this standard.

TABLE II. CHEMICAL COMPOSITION AND MAIN COMPOUNDS OF SULFATE-RESISTING PORTLAND CEMENT*

Oxides composition	Content %	Limits of Iraqi standard No.5/1984
CaO	62.15	---
SiO_2	19.88	---
Al_2O_3	3.5	---
Fe_2O_3	4.7	---
MgO	3.23	< 5.00
SO_3	1.84	< 2.50
Na_2O	0.26	
K_2O	0.51	
L.O.I.	1.25	< 4.00
Insoluble residue	0.80	< 1.5
Lime Saturation Factor	0.928	0.66-1.02
Main compounds (Bogue's equations)		
C_3S	54.51	---
C_2S	18.77	---
C_3A	1.51	< 3.50
C_4AF	14.14	---

* Chemical analysis wase carried out in the Karbala Laboratory

TABLE III. PHYSICAL PROPERTIES OF CEMENT

Physical properties		Test results	Limits of Iraqi standard No.5/1984
Surface area (Blaine) m^2/kg		282	≥ 250
Setting time (Vicat)	Initial setting, hrs: min	3:51	≥ 45 min
	Final setting, hrs: min	6:20	≤ 10 hrs
Compressive strength, MPa	3 days	23.7	≥ 15.00
	7 days	27.9	≥ 23.00
Soundness (autoclave) %		0.13	≤ 0.8

4) Coarse Aggregates

All mixtures contained local river gravel broken to a maximum size of 12.50mm as Coarse Aggregates (CA). The grading of CA corresponds to the Iraqi standard IQS No.45/ 1984 [15]. The CA properties were determined at the Karbala construction laboratory.

TABLE IV. CHEMICAL ANALYSIS OF SILICA FUME*

No.	Components	Silica fume %	ASTM C1240 limitations
1	CaO	1.22	
	SiO_2	91.05	≥ 85
	Al_2O_3	0.018	
	Fe_2O_3	0.012	
	MgO	0.01	
	SO_3	0.225	
	Na_2O	0.205	
	K_2O	0.155	
	Loss on ignition	2.975	≤ 6
	Moisture content	0.68	≤ 3
2	Activity index with Portland cement at 7 days	132.4	≥ 105
	Percentage retained on 45µm (No. 325) sieve, max, %	7	≤ 10
	Surface area (Blaine) m^2/kg	20000	≥ 15000

*The tests was carrying by the manufacturer

5) Silica Fume

Silica fume is a by-product of the production of silicon composites in electrical arched furnaces and may be utilized as a cementitious additive to improve the performance of concrete [16]. Densified micro-silica fume from Mega-Add MC (D) type was utilized in this study. Its Pozzolanic activity index is 132.4% after 7 days. Table IV displays the chemical and particular surface of the utilized silica fume, which conforms to ASTM C1240 [17].

6) High-Range Water Reducing Admixture

As shown in Table V, this additive belongs to the 3rd generation of superplasticizers. The admixture satisfies the standards of ASTM C 494 type G [18].

TABLE V. TECHNICAL DESCRIPTION OF THE ADDITIVE*

Chemical Base	Polycarboxylic ether based
Appearance/color	Amber homogenous liquid
Density	1.082 - 1.142 kg/liter, at 20°C
Chlorine content%	< 0.1
Alkaline content%	< 3
Recommended dosage	(0.5 - 1.5) of binder weight %

*Manufacturer data sheet

7) Water

Tap water was utilized for mixing and curing. The molten salts comprise fewer than one thousand parts per million. Distilled water was utilized for concrete mixing and curing.

8) Steel Fibers

Micro-steel fibers of the RC 59/13 BN type, with low carbon content, and with both straight ends were utilized. The fibers have a length of 13mm, diameter of 0.22mm, aspect ratio of 59, tensile strength of 2850MPa, and density of 7.85g/cm^3.

B. Mix Proportion

Authors in [3] have invented a sustainable binder known as Pozzolime. This binder consists of hydrated-lime, silica-fume; and does not include Portland cement. Table VI displays the proportions chosen for two Pozzolime mixtures, mix1 and mix2, based on the work of [3]. Using a small quantity of cement in mix2 hastened setting time. Firstly, 6 cubes were tested for compressive strength (f_{cu}) for each mix, and the results show that the value of f_{cu} for mix2 was 15.4 and 18.3MPa for age of 7 and 14 days respectively, while the f_{cu} for mix1 was 16.6 and 18.6MPa respectively. So, mix1 was chosen for the rest of the experimental work.

TABLE VI. POZZOLIME CONCRETE MIX PROPORTIONS AND PROPERTIES

Mixing	Materials								
	Hydrate lime (kg/m^3)	Cement (kg/m^3)	Silica fume (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	W/B ratio by wt.	HRWR by wt. of cement (%)	Slump mm	Compressive strength, 28 days (MP)a
Mix1	225	-	225	625	945	0.45	2.9	100	24.3
Mix2	310	25*	110	600	940	0.5	2.5	115	23.8

* for accelerated setting time

C. Casting and Curing of Specimens

All steel molds (cylinders and cubes) were cleaned and their inside was completely lubricated to prevent the concrete from adhering to the molds after setting. The concrete was poured in two layers before being compacted with a tamping rod or vibrating machine to exclude as much air as possible [19-21]. The samples' top surfaces were then troweled, and in order to avoid the loss of mixing water and moisture from the top surface and plastic shrinkage breaking, they were protected with polythene sheets for 24 hours.

Fig. 1. The tested specimens.

The samples were then demolded and completely submerged in tap water until testing time. The curing schedule for pervious concrete was 7 and 28 days of water curing. Figure 1 shows the tested specimens. Control specimens were also used in this research, so the total samples used were 9 cubes (10×10×10cm) for the density test, 27 cubes (10×10×10cm) for the compressive strength test, 27 cylinders (30×15cm) for the splitting tensile strength test, and 27 cylinders (30×15cm) for the modulus of elasticity test.

III. RESULTS AND DISCUSSION

A. Dry Density

Concrete's dry density following ASTM C138 [22] was determined using a cylinder mold. The specimens were evaluated after 28 days of water curing. The density of hardened concrete was determined using the subsequent procedures:

$$\gamma_{dry} = W_{dry} / Vol \quad (1)$$

where γ_{dry} is the dry density (kg/m^3), W_{dry} the oven-dry mass (kg), and Vol the volume of the specimens (m^3).

B. Compressive Strength

Compressive strength testing was determined in accordance with the BS EN 12390.0 [23] using a standard hydraulic digit ELE machine of 2000kN capacity at a loading rate of about 0.30MPa/s. At each test, the average value of 3 tested cubes was determined. The tests on Pozzolime concrete were conducted after 7 and 28 days of curing.

C. Splitting Tensile Strength (f_{ct})

Splitting tensile strength tests were based on ASTM C 496/C496M-(2011) [24]. A hydraulic digital testing ELE machine of 2000kN capacity was used to load the cylinders constantly up to failure at a loading rate of 2.2kN/sec. The mean splitting tensile strength was calculated using the average of 3 cylinders.

D. Modulus of Elasticity (E_c)

The modulus of elasticity of concrete (E_c) was tested using 3 concrete cylinders in accordance with ASTM C-469-(2002), [25]. E_c is calculated from the stress-strain diagram using a compress meter gauge with a length of 20cm and an accuracy of 0.001mm. The load was applied at a steady rate up to 40% of the maximum load.

All laboratory tests values for concrete mix1 are shown in Tables VII and VIII.

TABLE VII. TEST RESULTS OF CONCRETE MIX1

Property	Steel fibers (%)	Density (kg/m^3)	Increase in density (%)
Fresh density	0	2283	Ref.
Fresh density	0.5	2288	0.2
Fresh density	1	2292	0.4
Dry density	0	2250	Ref.
Dry density	0.5	2270	0.9
Dry density	1	2285	1.6
Oven density	0	2150	Ref.
Oven density	0.5	2200	2.3
Oven density	1	2225	3.5

Table VII indicates that the steel fiber percentage has a small effect on the fresh density: the increase of the percentage increased the fresh density by about 0.2, and 0.4% for added steel fiber percentage of 0.5 and 1% with respect to the reference specimens. Also, the steel fiber percentage has a small impact on dry density. Steel fibers increased dry density by about 0.9 and 1.6% for 0.5 and 1% added steel fiber percentage. Steel fibers had a higher impact on the oven density: steel fibers increased the oven density by about 2.3 and 3.5% for 0.5 and 1% added steel fiber percentage. Figure 2 shows the impact of steel fiber percentage on concrete density.

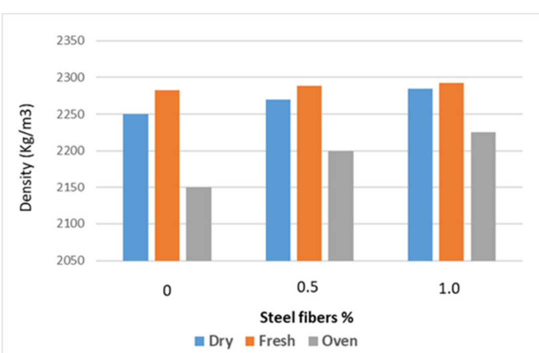

Fig. 2. The impact of steel fiber percentage on concrete density.

Table VII indicates that the steel fiber percentage has an important impact on compressive strength: steel fibers increased compressive strength by about 2.4 and 16.3% when 0.5 and 1% steel fibers were added at curing age of 7 days. This is comparable to [7], which shows that the percentage of 2% steel fibers increased the compressive strength by about 10.8%. Adding steel fibers increased the compressive strength by about 4.1, and 37.6% for 0.5 and 1% steel fiber addition at 14 days. At 28 days, the respective increase percentages were 4.9 and 12.8%. Figure 3 shows the effect of steel fiber percentage on concrete compressive strength at various ages.

TABLE VIII. RESULTS OF LABORATORY TESTS FOR CONCRETE MIX1

Property	Steel fiber (%)	Result (MPa)	Increase (%)
f_{cu}, 7 days	0	16.6	Ref.
	0.5	17	2.4
	1	19.3	16.3
f_{cu}, 14 days	0	18.6	Ref.
	0.5	22.7	4.1
	1	25.6	37.6
f_{cu}, 14 days	0	24.3	Ref.
	0.5	25.5	4.9
	1	27.4	12.8
f_{ct}, 7 days	0	2.11	Ref.
f_{ct}, 14 days	0.5	2.36	11.8
f_{ct}, 28 days	1	2.6	23.2
E_c, 7 days	0	23800	Ref.
E_c, 14 days	0.5	24200	1.7
E_c, 28 days	1	25000	5

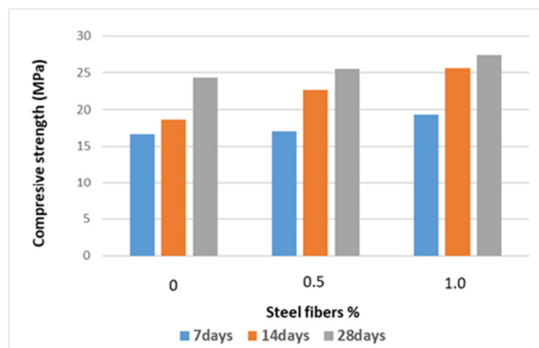

Fig. 3. The impact of steel fiber percentage on concrete compressive strength at various ages.

Also, Table VIII indicates that the steel fiber percentage has a significant impact on splitting tensile strength (f_{ct}) for 28 days curing age. Steel fiber 0.5 and 1% addition increased f_{ct} by about 11.8 and 23.2%. Finally, the addition of steel fibers has an impact on E_c after 28 days of curing. Steel fiber 0.5 and 1% addition increased E_c by about 1.7 and 5%.

IV. PARAMETRIC STUDY

Figures 4, 5, 6, and 7 indicate the impact of steel fiber percentage on density, compressive strength, splitting tensile strength, and modulus of elasticity respectively. The relation between the steel fibers percentage and splitting tensile strength was linear, while the relation between steel fiber percentage and compressive strength and modulus of elasticity was nonlinear for specimens cured for 28 days.

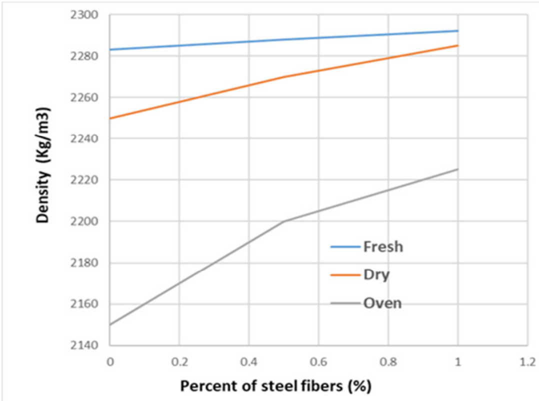

Fig. 4. Impact of steel fiber percentage on density.

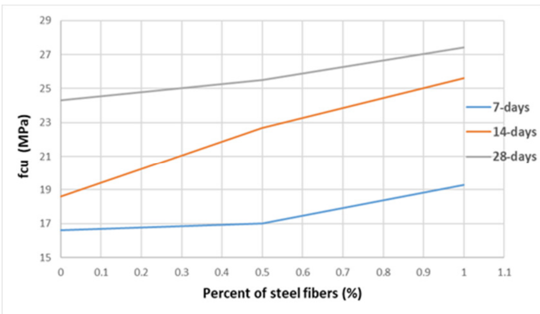

Fig. 5. Impact of steel fiber percentage on compressive strength.

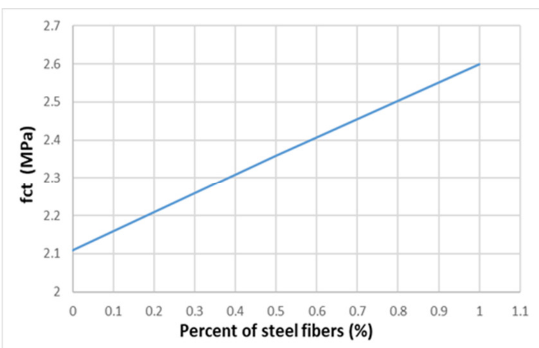

Fig. 6. Impact of steel fiber percentage on splitting tensile strength after 28 days of curing.

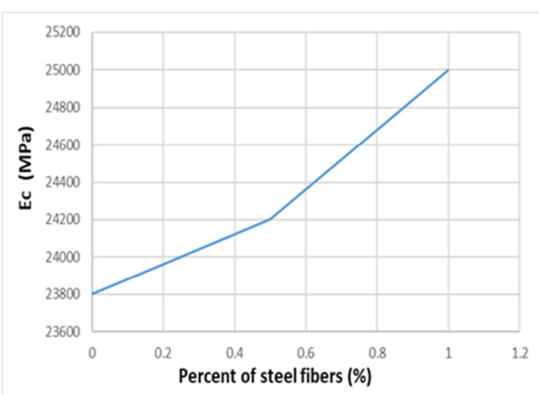

Fig. 7. Effect of steel fiber percentage on the modulus of elasticity after 28 days of curing.

V. Conclusions

- Steel fiber percentage had a minor influence on fresh density. Adding 0.50 and 1.0% steel fiber to the reference specimen enhanced the fresh density by 0.2% and 0.4% respectively.
- Steel fiber percentage had a marginal impact on dry density. Adding 0.5 and 1.0% steel fibers to the reference specimen raised the dry density by 0.9% and 1.6% respectively.
- Steel fiber percentage had a larger influence on oven density. Adding 0.5 and 1% steel fibers raised oven density by 2.3% and 3.5% respectively.
- Steel fiber percentage had an important impact on compressive strength. Adding 0.50 and 1.0% steel fibers increased compressive strength by 2.4% and 16.3% respectively, after 7 days of curing. Adding 0.50 and 1.0% steel fibers increased compressive strength by 4.1% and 37.6% at 14 days and 4.9% and 12.8% at 28 days.
- Steel fiber percentage had a substantial influence on splitting tensile strength at 28 days. Adding 0.50 and 1.0% steel fibers enhanced splitting tensile strength by 11.8% and 23.2% respectively.
- Steel fiber percentage affects the modulus of elasticity at 28 days. Adding 0.50 and 1.0% steel fibers increased the modulus of elasticity by 1.7% and 5% respectively..

VI. Recommendations for Future Work

- Studying eco-friendly zero-cement concrete proportions and properties under the effects of high-temperature.
- Studying slurry Infiltrated Fiber Concrete (SIFCON) proportions and properties under the effects of high-temperature.

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