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Optimum Steel Fiber Content of High Strength Pozzolime Concrete

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HIGHLIGHTS

- Pozzolime concrete was reinforced with hooked-end steel fiber at (0.5,1.0 ,1.5, and 2) percent volume fractions.
- The presence of steel fibers has a significant negative effect on the workability of all volume fractions tested.
- The maximum compressive and flexural strength was acquired, with the addition of 1.5 percent.
- The 1.5 percent volume fraction could be considered as the optimum fiber content.

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ABSTRACT

Pozzolime is a promising alternative binder, compared to Portland cement because of its low CO_2 emission. it is produced by mixing hydrated lime, silica fume, and fly ash. Fiber is added to concrete to improve the durability, mechanical properties of the structure, and others. In this study, high-strength Pozzolime concrete was reinforced with hooked-end steel fiber which was added as fractions of volume of 0.5, 1, 1.5, and 2%. Optimization for fiber content was performed according to the workability and strength of the fiber-reinforced mixture. Obtained results showed that the compressive strengths at 14d and 90d increased by 71.4% and 58.3% respectively when adding 1.5% steel fiber. Correspondingly, the 14d, 28d, and 90d flexural strength of pozzolime concrete increased by 170.4%, 203.2%, and 191.4% respectively at 1.5 % and a further increase in fiber content caused a reduction in strength. The finding presented in this research confirmed that the volume fraction (1.5%) can be considered as the optimum content.

1. Introduction

In recent years, global interest in sustainable constructional materials and environmentally friendly is grown. Therefore, there is a critical need for new alternative constructional-binders to replace conventional cement (*e.g.*, Portland cement) [1]. Currently, researchers are being encouraged to consider further options, one of which is the re-adopt of lime-Pozzolana systems. Lime could be regarded as an environmentally-sound binder because of its low energy requirements, minimal CO_2 emissions during manufacturing, and CO_2 preoccupation via carbonation during setting [2]. Lime-natural Pozzolana is a building material was used in masonry a long time ago [3]. Due to their slow setting and hardening, the usage of lime-natural pozzolana has been discontinued throughout the history of inorganic binders. Since Portland cement are quick to set and had high strength in the early ages, utilization of natural pozzolan-lime binding material was drastically reduced after its invention in the 19th century. In the last 50 years, the environmental consequences of the Portland cement manufacturing process had prompted an increase in interest in lime-natural pozzolan cement [4]. In Iraq Pozzolime, a novel sustainable binder made from hydrated lime, silica fume, and fly ash, has been developed by Kadum et al [5]. The conceptualize of Pozzolime is based on the pozzolanic reaction between supplementary cementations materials, SCM and calcium hydroxide to produce calcium silicate hydrates similar to that produced by Portland cement hydration. By the following equation, the Pozzolan reaction could be expressed:

$$3\mathrm{Ca}\ (\mathrm{OH})\ 2 + \mathrm{SiO2} = 3\mathrm{CaO} \cdot \mathrm{SiO2} + 3\mathrm{H2O}\ \text{or}\ \mathrm{C3S2H3} \qquad (1)\ [6]$$

Small and disconnected fibers were utilized for thousands of years to strengthen brittle materials. The Egyptians employed straws for instance in ancient times to enhance the crack resistance of sun-dried muds that were used to build huts [7]. The

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concept of incorporating steel fibers into concrete dates back to the 1800s when metallic waste was included in the mix [8]. The inclusion of steel reinforcing bars into concrete can prevent failure after crack and greatly increase the ductility and strength of the concrete material. Several studies have demonstrated that adding fibers, particularly steel fibers, to reinforced concrete can decrease or perhaps even eliminate the need for traditional primary reinforcement in some situations [9,10,11]. Steel fibers have been shown to increase post-cracking tensile response and crack control properties in reinforced concrete [12]. Mechanical strength of composite materials can also be increased by the use of deformed fibers, such as hooked, corrugated and twisted fibers. Deformed steel fibers reported can provide three to seven times greater fiber-matrix bond strength than that of straight fibers. The extent to which the mechanical characteristics are improved relies on several aspects such as fiber geometry, fiber length, cure conditions, and fiber length [13]. The fibers were often added to FRCC as a volumetric ratio (V*f*)of the mix limited, up to3%, to overcome mixing and casting issues such as balling and floating of the fibres [14]. The SFRC concept is simple. Concrete is weak in tension and reinforcing bars are only continuous at some specific positions, the tensile response of conventionally reinforced concrete is increased only in the reinforcement direction. Steel fibers, however, are randomly and discontinuously dispersed these features allow cracks to be bridged through the fibers in any orientation and allow better stress transport through all cracks, and enhanced post-cracking shear and flexural resistance [9]. In addition, fiber bridging permits the control of crack openings to allow more cracks to form. As a result, crack width and spacing are reduced, improving post-cracked ductility and energy absorption capacity [9, 15, 16, and 17]. In tensile stress, SFRC only fails after the fracture in the fibre or is pulled from the matrix [18]. Compressive stress, like the tensile response, mainly enhances post-peak ductility and toughness with the addition of steel fibres [19]. As previously stated, despite the numerous advantages of steel fiber on cement-based materials, such as improving in mechanical performance, increase post-cracking tensile response and controlling of crack of cement concrete, etc., however, the effects of steel fiber on new binders such pozzolimehas never been used before. Therefore, in order to get the additional information and to gain a better knowledge of the behavior of Fiber-reinforced Pozzolime concrete, this study aims to investigate the influence of the addition of hooked end steel fibers on its properties.

2. Materials, Mixes and Methods

2.1 Materials

The Silica fume and the Fly Ash were used as two kinds of materials for cementation. The chemical composition and physical properties of each material were determined following ASTM C1240 [20] and ASTM C 618 [21], respectively. Hydrated lime compatible with ASTM C821 [22] was used for the production of pozzolime. The chemical and physical characteristics of the material are shown in Table 1. To modify the workability of the Pozzolime concrete mixtures conforming to ASTMC494 [23] type F, high-range water-reducing admixture commercially known as Viscocrete- 5930 was used. In this experiment, a coarse aggregate with a maximum particle size of 14 mm and a fine aggregate with a 2.25 fineness modulus was used. The specific gravity and water absorption of course and fine aggregates were 2.65 and 0.05 percent, and 2.67 and 1.6 percent, respectively. Hooked-end steel fiber was used for this purpose. Table 2 lists the properties of the fiber used. The properties of steel fiber were in accordance with ASTM A820 [24].

Table 1: Chemical and physical properties of the binder materials

No.		property	HL*	SF*	FA*
1	**Oxide content%**	CaO	86.44	0.58	0.98
		SiO2	……	94.58	65.65
		Al2O3	……	0.1	17.69
		Fe2O3	……	0.06	5.98
		MgO	3.25	0.22	0.72
		SO3		0.11	0.19
		Na2O		0.21	1.35
		K2O		0.35	2.99
		L.O.I		1.98	3.1
2	**Surface Area (Blaine)m2**		1200	20000	773

HL*=Hydrated Lime, SF*=Silica fume, FA*=Fly ash. *Tests were carried out by the Iraq Geological Survey.

Table 2: Hooked-end steel fiber features

Property	Length, mm	Diameter, mm	Aspect ratio1/d	Density, kg/m3	Tensile Strength, MPa	Modulus of Elasticity, GPA
Value	35	0.6	58	7800	1000	203

*As given by manufacturer /Hebei Yusen Metal Wire Mesh Co., Ltd.

2.2 Pozzolime mixtures

A reference mix, M0, was produced with 1: 1 by weight Lime to Pozzolana ratio. Table 3 lists the mixed details. The four-volume percentages of hooked-end steel fibers were strengthened to provide mixtures: 0.5, 1, 1.5 and 2percent, respectively M0.5, M1.0, M1.5, and M2.0.

Table 3: Detail of mixtures

Mix	Binder, kg/m3			Aggregate, kg/m3		Water, kg/m3	Steel fiber, kg/m3	W/B By wt	HRWR by wt of binder	Vf%
	HL*	SF*	FA*	Fine	Coarse					
$M_{0.0}$	200	120	80	640	960	152	0.0	0.38	1.65	0.0
$M_{0.5}$	200	120	80	640	960	152	39.25	0.38	1.77	0.5
$M_{1.0}$	200	120	80	640	960	152	78.5	0.38	1.85	1.0
$M_{1.5}$	200	120	80	640	960	152	117.75	0.38	1.90	1.5
$M_{2.0}$	200	120	80	640	960	152	157	0.38	2.00	2.0

HL*=hydrated lime, SF*=silica fume, FA*=fly ash

2.3 Testing program

Table 4 shows the carried-out tests according to the shown standard methods, types of specimen, and age of test for the fresh and hardened Pozzolime mixtures.

Table 4: Fresh and hardened Pozzolime concrete tests

Test	Adopted standard	Specimen type	Dimensions, mm	Age of test, days
Slump	ASTM C143 [25]	---	----	----
Compressive Strength	BS EN 12390-3 [26]	Cube	100*100*100	14, 28, 56 and 90
Flexural Strength	ASTM C78 [27]	Prism	400*100*100	14, 28 and 90

3. Results and discussion

3.1 Workability

The slump test was carried out on fresh mixes to investigate the effect of steel fiber reinforcement on the workability of Pozzolime concrete. Figure 1 illustrates the average slump values. It is obvious to see that a 139 mm slump was recorded when no fibers were added into the Pozzolime concrete, mix $M_{0.0}$. The slump values started to decrease when steel fibers were added for mixes $M_{0.5}$, $M_{1.0}$, $M_{1.5}$, and $M_{2.0}$. The reductions in slump value concerning $M_{0.0}$ were; 10, 16.5, 23, and 29.5% respectively. The loss in a slump is mainly due to increased internal friction of ingredients and the balling of fibers. It is worth mentioning that this slump loss took place despite the dosage of HRWR was being increased.

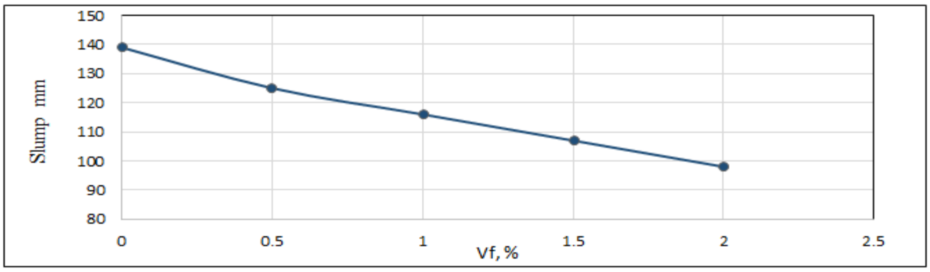

Figure 1: Effect of steel fibres on a slump of Pozzolime concrete mixtures

3.2 Compressive Strength

The compressive strength of Pozzolime concrete with and without being reinforced with steel fibers are listed in Table5 and shown in Figure 2.

Table 5: Results from compressive strength for studied Pozzolime concrete mixes

Mix	Volume fraction of fiber, Vf	Compressive strength MPa, at age:				The ratio strength gain, % for age:			
		14d	28d	56d	90d	14d	28d	56d	90d

$M_{0.0}$	0.0	38.8	42.6	45.2	48.9	----	----	----	----
$M_{0.5}$	0.5	48.5	50.4	51.3	53.2	25.0	18.3	13.5	7.2
$M_{1.0}$	1.0	50.6	56.7	58.9	63.1	30.4	33.1	29.4	22.9
$M_{1.5}$	1.5	66.5	72.7	75.8	78.9	71.4	70.7	67.3	58.3
$M_{2.0}$	2.0	58.4	65.6	68.8	70.6	50.5	53.9	48.7	42.3

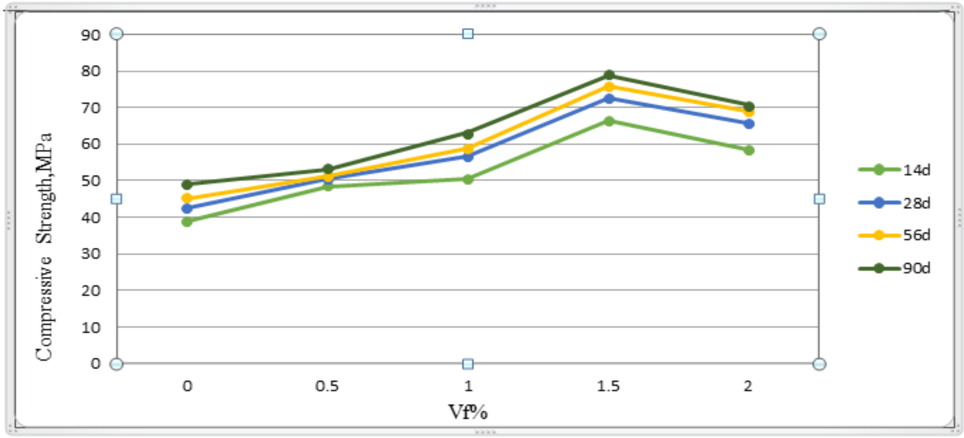

Figure 2: Influence of steel fibres on the compressive strength of pozzolime concrete

According to Table 5, it can be observed that there is always a gain in compressive strength with the increase in fiber content. This increase is understandable due to the higher density of steel added to concrete and caused more densification of the composite. Moreover, the inclusion of fibers was more effective in improving strength at an early age, 14 days, than other ages for all fiber contents. The gain in strength ratio is the increase in strength of fiber-reinforced mixes to the strength of reference mix M0, non-fibrous, at the specified age. Based on this ratio, it can be concluded the mix M1.5, which has Vf =1.5%, has shown the highest compressive strength increase at all ages. On the other hand, Mix M2.0, which has a higher Vf, exhibited a lower gain ratio and that could have resulted from the higher loss of workability which means higher content of entrapped air. Also, the higher possibility of fiber balling and improper bonding could be another reason.

3.3 Flexural Strength

The results of the flexural strength test on Pozzolime prism specimens are displayed in Table 6 and Figure 3. The same trend that was outlined for compressive strength is observed here. Mix $M_{1.5}$ also showed the highest gain in flexural strength ratio for all test ages. Therefore, this volume fraction could be considered the optimum fiber content that yields the best improvement concerning strength. In general, the inclusion of fibers in Pozzolime mixes caused a better enhancement in flexural strength results than those of compressive ones. This observation indicates that the role of fibers here is not the only densification but also crack arresting.

Table 6: Results of flexural strength for studied Pozzolime concrete mixes

Mix	**Volume fraction of fiber, Vf**	**Flexural strength MPa, at age:**			**The ratio strength gain, % for age:**		
		14d	28d	90d	14d	28d	90d
M0.0	0.0	2.7	3.1	3.5	----	----	----
M0.5	0.5	3.5	5.0	5.8	29.6	61.3	65.7
M1.0	1.0	5.1	5.9	7.0	88.9	90.3	100
M1.5	1.5	7.3	9.4	10.2	170.4	203.2	191.4
M2.0	2.0	7.0	7.7	8.4	159.3	148.4	140

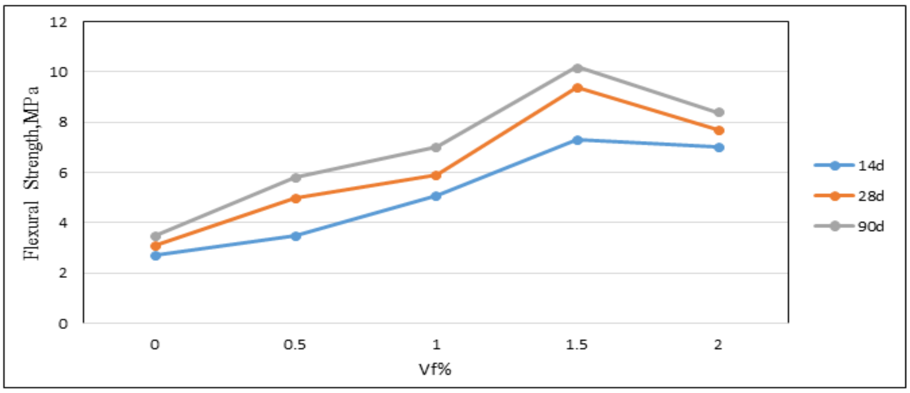

Figure 3: Influence of steel fibre on Pozzolime concrete's flexural strength

4. Conclusions

The following conclusions can be outlined based on the present data:

1) The steel fibers when used as reinforcement in Pozzolime concrete significantly reduce its workability. The slump values started to decrease when steel fibers were added for mixes according to [28] that conclude the inclusion of fibers (of any kind) reduced slump flow. It is worth mentioning that this slump loss took place despite the dosage of HRWR was being increased.
2) There is always a gain in strength with the increase in fiber content. The inclusion of fibers was more effective in improving strength at an early age, 14 days than other ages for all fiber contents.
3) The inclusion of fibers in Pozzolime mixes caused a better enhancement in flexural strength results than compressive strength results. These results indicate that fibers have a dual role in tensile stresses: densification and crack arrest.
4) Based on the gain in strength ratio, the 1.5% volume fraction could be considered as the optimum fiber content which yields the best improvement concerning strength.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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