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Evaluating the effect of macro-synthetic fibre on the mechanical properties of roller-compacted concrete pavement using response surface methodology

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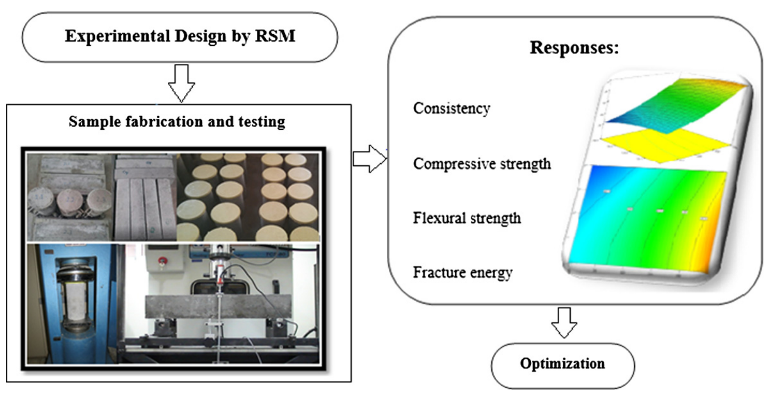
HIGHLIGHTS

- This paper deals with macro-synthetic fibre reinforced roller compacted concrete.
- Response surface methodology was employed among the different range of cement, water and fibres.
- Experimental results under consistency, compression and bending test are reported.
- The addition of fibres does not significantly affect the compressive strength of RCCP.
- Hardening of the post-cracking zone is expectable for high-flexural strength.

GRAPHICAL ABSTRACT



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ABSTRACT

This study provides guidance for the design of macro-synthetic reinforced roller-compacted concrete pavement (RCCP) with appropriate consistency and enhanced mechanical performance for pavement applications. The response Surface Methodology was used to study the effects of fibres (0–0.5%), cement (300–350 kg/m^3) and water (120–150 kg/m^3) on the Vebe time, compressive and flexural strength, and fracture energy of RCCP. The interaction between these three factors were examined modelled using a statistical regression model, showing that the addition of macro-synthetic fibres to the RCCP mixture linearly reduces the RCCP consistency (Vebe time), while fibres do not significantly affect the compressive strength. Based on three-point bending test results on notched beam, fibre, cement, and water linearly affect the flexural strength. However, fibre tended to influence the fracture energy more significantly than flexural strength. It was found that the mortar-fibre interaction highly affects the RCCP post-cracking behavior Therefore, hardening of the post-cracking zone in the load-CMOD curve is expectable for high-flexural strength RCCP at a high volume fraction of fibres.

1. Introduction

Roller-compacted concrete (RCCP) is a zero-slump and stiff-dry mixture which is usually placed with an asphalt paver and compacted by conventional vibratory roller compactors to achieve

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the required density. RCCP consistently has a slightly lower cement content than conventional concretes of similar strength. Nowadays, RCCP is used for any type of industrial or heavy-duty pavement and has advantages including cost saving as a result of the construction method and the increased placement speed of the pavement [1,2]. Therefore, the use of RCCP pavement has become more and more popular in recent years.

Typically, the RCCP is constructed without joint. It needs neither forms nor surface finishing, nor does it contain bar reinforcing and dowels. Consequently, considering a proper mix design, load transfer can be achieved through aggregate interlock [2,3]. Nevertheless, RCCP can be reinforced with fibres in order to improve the durability, flexural strength, load transfer capacity, and so on [4–7].

Recently, many studies have been performed on concrete reinforced with different type of fibres which are mainly of four type: glass, natural, metal, and synthetic fibres [8–12]. The potential of fibres to improve concrete properties/performance depends on different factors such as volume fraction, type, aspect ratio, surface friction, and tensile strength of fibre. Synthetic fibres are generally of four types: aramid, polyolefin, acrylic, and carbon, but as regards size and application, they are either micro-synthetic (low elasticity modulus, 5–10 μm in diameter, and 5–30 mm in length) used to restrain the early-age shrinkage and suppress shrinkage cracking or of the macro-synthetic (30–60 mm in length and 0.6–1 mm^2 in cross-sectional area) utilized to improve the concrete's relatively low tensile strength and post-cracking behavior [13–15].

A summary of the numerous recent studies on the effects of different types of fibres on the concrete's mechanical properties is shown in Table 1. Different compressive strength results show that it is highly affected by the type, aspect ratio, and volume fraction of fibre as well as the concrete type. It is worth mentioning that in the concrete compressive strength test, macro fibres can cause minor cracks on the specimen surface during failure, while the plain concrete fails catastrophically, which means that the fibres still held the concrete together at the failure load [16]. The amount of fiber added has a significant influence on the tensile and flexural properties as well as the failure mode of fibre-reinforced concrete. In their research on the amount of fibres added to concrete, Liber et al. indicated that in low polypropylene fibre volume fractions (below 0.2% by volume fraction), the mechanical properties of concrete do not significantly change. They concluded that the least percentage for considerable improvement in the concrete flexural performance is 0.4% [17].

2. Objectives

There are numerous studies on the mechanical properties of fibre-reinforced concrete, Nevertheless, our understanding of what exactly constitutes an optimal percentage of fibres capable of producing maximum mechanical performance in RCCP with respect to consistency remains quite limited. Accordingly, this research was conducted to study the effects of fibres on the mechanical properties of RCCP with a specified range of cement and water using the Surface Response Methodology to achieve the following goals:

- Studying the effects of macro-synthetic fibres on the consistency and compressibility of RCC for use in pavement application.
- Presenting an RCCP compressive strength prediction model in order to evaluate the effects of these parameters, and find their interactions.
- Studying the performance of fibre in bending using the notched three-point bending test, investigating its effects on pre-cracking concrete behavior by finding the flexural strength, and comparing the post-cracking behavior of the fibre-reinforced RCCP in the presence of different mixture proportions through calculating the fracture energy.
- Optimizing the appropriate water-cement-fibre combination in the fibre-reinforced RCCP considering an acceptable efficiency for use in the road pavement to reach the maximum flexural strength, fracture energy, and compressive strength.

3. Materials and specimen preparation

The physical properties of siliceous aggregates are listed in Table 2. The particle size distribution of aggregates with nominal maximum aggregate size (NMAS) of 19 mm is shown in Fig. 1. The selected gradation falls within the gradation range of Iran

Table 1
The summary of fibre's effect on mechanical properties as reported in the literature (Increase↑, Decrease↓, Not Significant N.S).

Authors	Year	Fibre properties			Concrete type	Compressive strength	Splitting tensile strength	Flexural strength
		Type	Length (mm)	Fibre volume Fraction (%)				
Fallah and Nematzadeh [18]	2017	Polypropylene	39	0.25, 0.75, 1.25	high-strength concrete	8%↑, 3%↑, 4%↓	(8, 9, 27)%↑	–
Hesami et al. [19]	2016	Polypropylene	60	0.10, 0.12	Self-compacting concrete	2%↑, 5%↓	(19, 27)%↑	(26, 33)%
Saidani et al. [20]	2016	Steel fibres	50	4% (by cement volume)	Normal concrete	2%↓	98%↑	–
		Polypropylene	50	4% (by cement volume)		5% ↓	65%↑	–
Afroughsabet and Ozbakkaloglu [21]	2015	Hooked-end steel	60	0.25, 0.5, 0.45, 1	High-strength concrete	(12, 14, 15, 19)%↑	(15, 22, 38, 57)%↑	(14, 28, 36, 61)%↑
Yew et al. [22]	2015	Polypropylene (twisted bundle)	54	0.25, 0.375, 0.5	Light weight concrete	(5, 11, 15)%↑	(8, 24, 33)%↑	(29, 31, 40)%↑
			30	0.25, 0.375, 0.5		(3, 10, 14)%↑	(10, 19, 27)%↑	(18, 22, 30)%↑
		-polypropylene (straight)	20	0.25, 0.375, 0.5		(4, 10, 14)%↑	(13, 14, 21)%↑	(6, 10, 20)%↑
Karadelis and Yougui [4]	2015	Steel	50	1.5	Roller-compacted concrete	N.S	–	24%↑
Hesami et al. [23]	2014	Steel	36	0.5	Pervious concrete	24% ↑	33%↑	19%↑
		PPS	54	0.3		28% ↑	37%↑	21%↑
		Glass	12	0.2		32% ↑	28%↑	17%↑
Pajak and Ponikiewski [24]	2013	Hook end steel	30	0.5, 1, 1.5	Self-compacting concrete	(34, 32, 20)%↑	–	55%, 151%, 339%↑