Gholami *et al. Int J Concr Struct Mater (2024) 18:9*
https://doi.org/10.1186/s40069-023-00647-8

International Journal of Concrete Structures and Materials

RESEARCH Open Access

Increasing the Length of Concrete Pavement Slabs Using Shrinkage Reducing Admixture and Polypropylene Fiber

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Abstract

Pavement engineers frequently employ concrete pavements because of their benefits such as extended lifetime, superior performance and durability, and so on. However, there are some disadvantages of these pavements such as shrinkage which may lead to cracking, warping, and limiting the length of the concrete pavement slabs. Shrinkage reducing admixture (SRA) and polypropylene fibers can be employed to prevent or control shrinkage cracking. In this study, increasing the length of concrete pavement slabs using shrinkage reducing admixture and polypropylene fiber was investigated. For mix compositions, two water–cement ratios of 0.35 and 0.4 were employed, and the percentages of SRA and polypropylene fiber utilized in mixes were 2% and 1% by weight of cement, respectively. Slump, compressive strength, third point flexural strength, electrical resistance, free and restrained shrinkage tests were carried out as the experimental programming to investigate the effect of these materials on concrete behavior and evaluate the amount of concrete pavement design parameters. Statistical analysis and RSM were used to determine the significance of each parameter and their interactions on concrete properties. It was observed that the use of SRA had no influence on workability; however, polypropylene fibers reduced the slump flow of concrete. Also, the use of SRA resulted in a decrease in mechanical properties. In addition, the use of polypropylene fibers considerably enhanced the energy absorption of concrete. Furthermore, on concrete containing SRA and polypropylene fiber, the magnitude of free and restrained shrinkage and crack width were reduced. Finally, the length and thickness of concrete pavement slabs were evaluated using the experimental results on the Tehran-Shomal freeway as a case study. The slab length could be increased by about 20% without any significant change in the slab thickness using SRA and polypropylene fiber in concrete mix composition. This can lead to an increase in construction speed, improve the durability of pavement and generally increase the quality of the concrete pavement.

Keywords Shrinkage cracks, Concrete slab length, Polypropylene fiber, Shrinkage reducing admixture (SRA), Statistical analysis, RSM plots

1 Introduction

Recently, concrete pavements are widely used in transportation infrastructure over flexible pavements because of their advantages such as suitable lifetime, good performance and durability, lower distresses during the lifetime (Embacher & Snyder, 2001). Because of using dowels, mesh in joint, and other reinforcement types, these pavements have much more initial costs than flexible pavements (University of Sheffield [UoS], 2005). Shrinkage is one of the drawbacks of concrete, which

Journal information: ISSN 1976-0485 / eISSN 2234-1315.

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occurs due to water evaporation from cement paste and causes volumetric loss of concrete, and subsequently more reinforcement is required (Mostofinejad, 2017). Warping and curling are other distress of concrete that mainly affect support conditions and pavement's slab. Drying shrinkage is one of the reasons for occurrence of these drawbacks (Ruiz et al., 2005). In addition, there is a relationship between warping and magnitude and rate of shrinkage (Chilwesa et al., 2019). Furthermore, because concrete pavements have wide surfaces, shrinkage cracks occur when they are exposed to environmental conditions, which is more crucial than other design criteria (Zhang & Li, 2001) and can decrease pavement capacity by up to 50% (Jafarifar et al., 2016).

Shrinkage reducing admixture (SRA) is a substance used to reduce shrinkage cracks in concrete without causing volumetric change (expansion) (Yazda Publication, 2014). It controls shrinkage by reducing capillary tension (Mehta & Monteiro, 2017). Maia et al. (2012) tried to find the influence of two types of SRA on the behavior of ordinary and high-performance SCC with W/C of 0.32 and 0.435. Retardation in cement hydration and reduction in initial temperature were observed using SRA in concrete. Also, the mechanical properties of concrete could be enhanced or diminished depending on the type of used SRA. Retardation in hydration of cement and initial setting time after using SRA in concrete were found by Chen et al. (2020). Kim and Lee (2018) investigated the effect of SRA in latex modified concrete and reported that using SRA caused an improvement on mechanical properties. However, it had no serious influence on slump. Deboodt et al. (2016) observed that SRA weakens the mechanical properties of concrete. But this admixture reduced shrinkage of concrete and its cracks based on their study. The effect of SRA on cement paste was investigated by Wehbe et al. (2017) and they reported that using SRA leads to weakness in electrical resistance. Decreasing electrical resistance at early ages of concrete and increasing it after hardening were concluded because of using SRA in concrete by Zuo et al. (2019). Hatami et al. (2017) stated using SRA has a positive effect on slump, durability and shrinkage properties of HPC.[1] Qiao et al. (2017) investigated the ions migration of concrete in the presence of SRA and declared that SRA helps in better ions' migration, especially on relative humidity between 40 and 80%. Zhang et al. (2023) conducted a study to investigate the impact of SRA on the performance of alkali-activated slag. Their findings revealed that the use of SRA resulted in a decrease in mechanical properties, hydration product formation, and the magnitude of drying shrinkage. This reduction in shrinkage is attributed to the decrease in surface tension and the number of generated pores. Sanjay et al. (2022) employed polycarboxylate as an SRA in self-compacting concrete and demonstrated its effectiveness in reducing various types of shrinkage. Furthermore, Wang et al. (2021) conducted a comprehensive study comparing the effects of MgO, polyvinyl alcohol (PVA) fiber, fly ash, and SRA on the frost resistance of concrete slabs. Their research indicated that all of these admixtures improved the resistance of concrete slabs against frost. Notably, fiber and SRA exhibited the highest and lowest effects, respectively, on frost resistance. in addition, fiber and fly ash enhanced the mechanical properties of the concrete, whereas the use of MgO and SRA led to reductions in both compressive and tensile strength. Moreover, Tang et al. (2023) reported a reduction in both shrinkage and deformation associated with creep in high-performance concrete based on their study.

Fibers are widely used as reinforcements to control crack width in concrete. There are no chemical reactions between fibers and cement or other components of concrete (Ramezanianpour et al., 2013); hence, fibers control and restrict cracks' width by bridging the opening cracks and transferring forces (Caggiano et al., 2016; Hsie et al., 2008; Ramezanianpour et al., 2013). The effect of shrinkage on edge curling and debonding of slab elements reinforced in bonded overlay were investigated by Chilwesa et al. (2019), who found that using fibers had no significant effect on the age of cracking, but it mainly reduced crack width. Due to the adsorption of cement paste to polypropylene fibers and the increase in its viscosity, a reduction in slump flow due to using these fibers in concrete with $W/C = 0.64$ was reported by Hsie et al. (2008). In addition, they concluded that using fibers created a connection between the layers of concrete elements and caused a decrement of drying shrinkage. Olaoye et al. (2013) realized that using fibers decreased slump flow due to creating restrict against the movement of concrete materials. Eren and Marar (2010) investigated the effect of steel fibers on the behavior of plastic shrinkage of concrete with two water–cement ratios of 0.54 and 0.43. They observed that compressive strength was decreased using these materials since not achieving the appropriate density in fiber-reinforced concrete. Also, the evaporation rate was increased using fibers, and it may lead to a decrease in the age of first-cracking. However, using these reinforcements caused a reduction in crack width and crack area. Decrease in mechanical properties of concrete using fibers was concluded by Ramezanianpour et al. (2013). They mentioned that it might happen because of increasing void content of transition zone and porosity of C–S–H without any volume

[1] High-performance concrete.

Table 1 Results of chemical analysis of cement

Chemical composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
Type II Portland cement (%)	21.84	4.56	3.52	63.01	3.60	1.75	0.18	0.53

change. In another study, Afroughsabet et al. (2015) found that using steel and polypropylene fibers improved the compressive and flexural strengths of HPC concrete, and they believed that it happened due to restrain micro-cracks and decrease in stress concentration. Improving compressive strength and electrical resistance of concrete containing polypropylene fiber and siliceous aggregates were reported by Kakooei et al. (2012). Bridging between the crack sides and the restraining movement were some reported reasons for this finding. Wang et al. (2019) focused on the effect of basalt and polypropylene fibers on the mechanical properties of high-performance concrete. They reported that using more percentage of PP fiber caused a slight improvement in compressive strength and significant improvement in flexural and tensile strength. Hossain et al. (2019) stated that using polypropylene fibers improves mechanical properties, decreases workability and mainly improves the ductility of recycled aggregate concrete. The effect of polypropylene fiber and rubber crumb on mechanical properties of concrete was investigated by Mo et al. (2020). They concluded that using polypropylene fibers had a conflicting effect on compressive strength, yet improved concrete ductility and dissipated the energy. In addition, the use of polypropylene fibers increased the energy required for compaction and weakened the bond between the cement paste and the aggregates. Bagheri et al. (2019) stated that there is no significant effect between the age of cracking and using fibers, but using fibers decreased crack width. Badogiannis et al. (2019) concluded that using fibers caused a reduction in the amount of shrinkage and delay in the age of cracking. Furthermore, fibers prevented concrete from creating and growing cracks due to connecting concrete pieces. Gong et al. (2018) found that using propylene fibers improves concrete durability against autogenous and drying shrinkage. In addition, Wang et al. (2022) conducted a study to examine the impact of MgO and PVA fiber on the abrasion and crack resistance of hydraulic concrete. Their research indicated that the incorporation of fiber into hydraulic concrete led to a notable enhancement in tensile strength, approximately by 10%, and a slight increase in both compressive strength and abrasion resistance. Furthermore, the utilization of fiber significantly prolongs the initial cracking time and substantially improved the concrete's resistance to cracking caused by drying. Furthermore, several researchers have posited that the incorporation of fibers into concrete can effectively mitigate shrinkage cracking and enhance its resistance to shrinkage (Choi et al., 2023; Zhou et al., 2023). Moreover, Chen et al. (2022) conducted a study examining the impact of varying lengths of polypropylene fiber in concrete. Their findings revealed an initial increase in both compressive and tensile strength upon the introduction of fibers, followed by a subsequent decrease. In addition, fibers were found to significantly enhance the concrete's resistance to shrinkage, with the 12-mm fiber demonstrating the most effective performance against shrinkage cracking.

Increasing the length of concrete pavement slab of jointed plain concrete pavement is a serious challenge that is restricted by drying shrinkage. Using SRA and polypropylene fiber is a suitable solution to control drying shrinkage, but these materials have a significant effect on other concrete properties that have been used in the concrete pavement design procedure, especially concrete slab thickness. So, it is necessary to investigate the effect of SRA and fiber on the mechanical and durability properties of concrete containing SRA and polypropylene fiber. Also, understanding the effects of fiber, SRA, W/C and their interactions is crucial to evaluate the pros and cons of using each material in concrete pavement. Finally, the effect of using SRA and polypropylene fiber on the length and thickness of the concrete pavement slab should be determined based on concrete properties. So, increasing the length of concrete pavement slabs using shrinkage reducing admixture and polypropylene fiber was investigated in this study. For this purpose, an experimental program and statistical analysis were used to determine the significance of each parameter on concrete properties. The RSM plots have key roles in achieving this aim. If shrinkage is controlled using these materials without causing serious weaknesses in the concrete, they can be used in concrete pavements to improve the durability and performance of pavements over time, increase the concrete slab length in jointed plain concrete pavements, improve the implementation rate, and reduce the number of joints and dowels.

2 Materials and Methods

2.1 Materials and Sample Preparation

In this study, the materials utilized in the concrete pavement of the Tehran-Shomal freeway were used.

Table 2 Physical properties of fine and coarse aggregates

Name	Density (g/cm^3)	Water absorption (%)
Gravel 9.5–19 mm	2.49	2.85
Gravel 6–12 mm	2.65	2.40
Sand 0–6 mm	2.67	2.00

Table 3 Chemical properties of SRA and superplasticizer

Name	Density (g/cm^3)	Nature	Active material %
SRA	0.9	Polypropylene glycol, non-ionic	90
Superplasticizer	1.08	Polycarboxylate, non-ionic	35

Table 4 Physical and mechanical properties of polypropylene fiber

Name	Compositions	Water absorption	Density (g/cm^3)	Tensile strength (MPa)	Modulus of elasticity (MPa)
Emboss fiber	Polypropylene, modified co-polymer	None	0.91	600	5500

A Type II Portland cement with a density of 3130 kg/m^3 was used in this study. The chemical composition of cement is shown in Table 1.

In addition, three types of aggregates were used: 9.5–19 mm gravel, 6–12 mm gravel, and 0–6 mm sand. The proportion of each type was 20%, 25%, and 55% of the total weight of aggregates, respectively. The physical properties of aggregates are represented in Table 2.

A shrinkage reducing admixture and polypropylene fibers was used to control and reduce shrinkage and crack width. In addition, the range of 50–90 mm was selected for slump, so a superplasticizer was used to achieve that. The chemical properties of SRA and superplasticizer are represented in Table 3. Also, Table 4 shows some physical and mechanical properties of the polypropylene fibers.

The mix composition was considered based on the national method for concrete mix design (Building & Housing Research Center, 2008) with two water–cement ratios of 0.35 and 0.4, and the amount of cement was 400 kg/m^3. It should be noted that the W/C of 0.35 was in accordance with the Tehran-Shomal freeway mix composition.

Also, the amount of shrinkage reducing admixture and polypropylene fibers was 2% and 1% by weight of cement, respectively. These percentages were identified as the optimum percentage of SRA and fiber by the producers. Table 5 shows the 8 concrete mix compositions examined in this study.

Furthermore, the experimental programming was planned as a full-factorial design with three different parameters and two levels in this study. The considered parameters were W/C (0.35 and 0.4), SRA (0% and 2%) and fiber (0% and 1%). Moreover, the age of specimens was defined as a block to investigate the significance of each parameter on concrete properties regardless of concrete age (see Table 5). A block is a source of variability that is not of primary interest in the research process, according to the statistical theory of experimental design.

Table 5 Concrete mix compositions (per cubic meter) for a full-factorial design run

Name	OPC 0.35	SRA 0.35	FIBER 0.35	SRA & FIBER 0.35	OPC 0.4	SRA 0.4	FIBER 0.4	SRA & FIBER 0.4
Run	1	2	3	4	5	6	7	8
W/C	0.35	0.35	0.35	0.35	0.4	0.4	0.4	0.4
Cement (kg)	400	400	400	400	400	400	400	400
Gravel 9.5–19 (kg)	375.6	375.6	375.6	375.6	365.3	365.3	365.3	365.3
Gravel 6–12 (kg)	469.5	469.5	469.5	469.5	456.6	456.6	456.6	456.6
Sand 0–6 (kg)	1032.8	1032.8	1032.8	1032.8	1004.6	1004.6	1004.6	1004.6
Water (kg)	140	140	140	140	160	160	160	160
Superplasticizer (kg)	2	2	3	3	1.6	1.6	1.6	2.3
SRA (kg)	0	8	0	8	0	8	0	8
Polypropylene fiber (kg)	0	0	4	4	0	0	4	4
Density (kg/m^3)	2372	2363	2375	2380	2344	2334	2297	2303
Slump (mm)	68	72	75	75	70	69	55	72

Fig. 1 Specimen mold before the test (Top) and molded concrete specimen under data acquisition (Bottom)

2.2 Test Method

Slump, compressive strength, flexural strength with center-point loading, electrical resistance, free shrinkage, and restrained shrinkage tests were done as an experimental program.

Compressive strength test was performed on 100*100*100 mm cubic samples at three ages of 7, 28, and 90 days (ISIRI 1608-3, 2015). Also, according to ASTM C293 (2016a) and ASTM C1018 (1997), center-point flexural strength was used to evaluate the flexural strength and toughness of concrete specimens. It has to be noted that the flexural specimens' size was 285*75*75 mm, which met the standard criteria. It was determined at three ages of 7, 28 and 90 days. In addition, electrical resistance was performed according to the Florida method (FM5-578, 2004) as a non-destructive test, so it was done on flexural samples at three ages of 7, 28 and 90 days. Evaluating free shrinkage by length change test was also applied in this study. The specimens' size was 285*75*75 mm as the maximum size of aggregates was 25 mm (ASTM C157, 2014).

Restrained shrinkage was one of the most important tests which was carried out according to ASTM C1581 (2016b). Eight standard molds were made based on the standard in this study. Fig. 1 represents some of these molds. Data collection was continued until the age of 60 days.

3 Results and Discussion

To evaluate the effect of SRA and fiber on design of concrete pavement, the results of experimental testing were first analyzed, and following that, the concrete pavements were designed based on the experimental outputs.

3.1 Slump Flow and Density

Results of the fresh properties of concrete were also represented in Table 2. As it can be seen, SRA had a slight effect on fresh properties of concrete. Furthermore, using polypropylene fibers caused a considerable reduction in the amount of slump flow which might be due to interlocking aggregates and fibers to each other that aggregates could not move and rearrange in concrete (Behfarnia & Behravan, 2014; Olaoye et al., 2013). Being a physical bond between the transition zone and fibers and absorption of a matrix on the surface of fibers might be another reason for this reduction (Hsie et al., 2008). In addition, increasing the W/C causes an increased workability of concrete. It could be because of increasing the water used in concrete mix composition by increasing the W/C at the same amount of cement used.

3.2 Mechanical Properties

The compressive and flexural strength results of all mixes are shown in Table 6. The W/C ratio was inversely related to mechanical properties. It might be due to increasing the volume of aggregates, reducing matrix and non-reacting water. Also, SRA had reduced mechanical properties which seems that the delay in cement hydration was due to the usage of SRA (Chen et al., 2020; Deboodt et al., 2016). Polypropylene fiber-reinforced concrete (FRC) has a different effect on mechanical properties. The reduction of mechanical properties on FRC might be due to an increase in the porosity of concrete, air content and concrete heterogeneity, and weakness in the transition zone (Eren & Marar, 2010; Ramezanianpour et al., 2013). However, the improvement of mechanical properties on FRC might be because of bridging between two sides of cracks and reducing stress concentration using fiber after increasing homogeneity of FRC using more superplasticizer (Afroughsabet & Ozbakkaloglu, 2015).

Furthermore, energy absorption was calculated for all FRCs by measuring the area under the load–deflection curve up to the first-crack deflection (Table 7). Energy dissipation has been mainly increased using

Table 6 Mechanical properties of all mix compositions

Concrete type	Age					
	7 days		28 days		90 days	
	Compressive Str. (MPa)	Flexural Str. (MPa)	Compressive Str. (MPa)	Flexural Str. (MPa)	Compressive Str. (MPa)	Flexural Str. (MPa)
OPC 0.35	42.88	7.44	53.58	8.36	57.97	9.14
SRA 0.35	39.15	7.41	51.34	7.65	53.19	8.59
FIBER 0.35	51.14	9.00	63.74	8.60	67.17	10.03
SRA & FIBER 0.35	47.72	7.53	57.24	9.01	61.82	9.54
OPC 0.4	34.14	6.79	46.66	7.54	51.04	7.79
SRA 0.4	33.07	6.73	44.71	7.12	48.24	7.29
FIBER 0.4	33.57	6.41	44.22	6.52	48.78	6.60
SRA & FIBER 0.4	37.37	7.01	52.16	7.07	55.18	7.35

Table 7 Results of evaluating toughness indexes of FRCs

Sample name	Age	I5	I10	I20
FIBER 0.4	7 days	2.097	2.448	2.923
	28 days	2.025	2.324	2.786
	90 days	1.89	2.006	2.204
FIBER 0.35	7 days	2.154	2.374	2.723
	28 days	2.09	2.333	2.644
	90 days	2.088	2.214	2.417

Table 8 ANOVA for selected factorial model: Compressive Strength

Source	Sum of squares	*df*	Mean square	F-value	*p*-value	
Block	3161.61	2	1580.81			
Model	2778.27	7	396.90	141.01	< 0.0001	Significant
A-W/C	1734.42	1	1734.42	616.19	< 0.0001	
B-SRA	23.46	1	23.46	8.33	0.0053	
C-Fiber	514.39	1	514.39	182.75	< 0.0001	
AB	183.73	1	183.73	65.28	< 0.0001	
AC	173.93	1	173.93	61.79	< 0.0001	
BC	47.16	1	47.16	16.75	0.0001	
ABC	101.18	1	101.18	35.95	< 0.0001	
Residual	174.51	62	2.81			
Lack of fit	36.48	14	2.61	0.9060	0.5583	Not significant
Pure error	138.04	48	2.88			
Cor total	6114.39	71				
R^2	0.9409	**Adjusted R^2**	0.9342		**Predicted R^2**	0.9203

polypropylene fiber in concrete. It could be because of bridging both sides of cracks using polypropylene fiber (Eren & Marar, 2010).

In addition, results of mechanical properties were imported into Design-Expert software to analyze data statistically. The significance of three effects (W/C, SRA & Fiber) on the response variable (compressive and flexural strength) was determined using the analysis of variance ($\alpha = 0.05$). Due to pass model adequacy checking, power transformation with Lambda of − 0.5 and constant of − 4 was used on flexural strength. Tables 8 and 9 show the output of using the ANOVA method on Design-Expert.

Also, the response surface plots (RSM) for mechanical properties are represented in Fig. 2. RSM plots represented that for a constant compressive strength, the percentage of polypropylene fiber can be decreased using a lower water–cement ratio. For example, concrete with W/C of 0.35 and without polypropylene fiber had similar behavior to concrete with W/C of 0.375 and 1% polypropylene fiber in compressive strength. In addition, using

Table 9 ANOVA for selected factorial model: flexural strength

Source	Sum of squares	*df*	Mean square	*F*-value	*p*-value	
Block	0.0464	2	0.0232			
Model	0.2600	7	0.0371	34.42	< 0.0001	Significant
A-W/C	0.1947	1	0.1947	180.38	< 0.0001	
B-SRA	**0.0000**	**1**	**0.0000**	**0.0194**	**0.8897**	
C-Fiber	**0.0002**	**1**	**0.0002**	**0.1450**	**0.7047**	
AB	0.0104	1	0.0104	9.64	0.0029	
AC	0.0326	1	0.0326	30.17	< 0.0001	
BC	0.0101	1	0.0101	9.36	0.0033	
ABC	0.0121	1	0.0121	11.24	0.0014	
Residual	0.0669	62	0.0011			
Lack of fit	0.0212	14	0.0015	1.59	0.1170	Not significant
Pure error	0.0457	48	0.0010			
Cor total	0.3733	71				
R^2	0.7953	**Adjusted R^2**	0.7722		**Predicted R^2**	0.7240

The values displayed in bold represent the non-significant parameters in the model

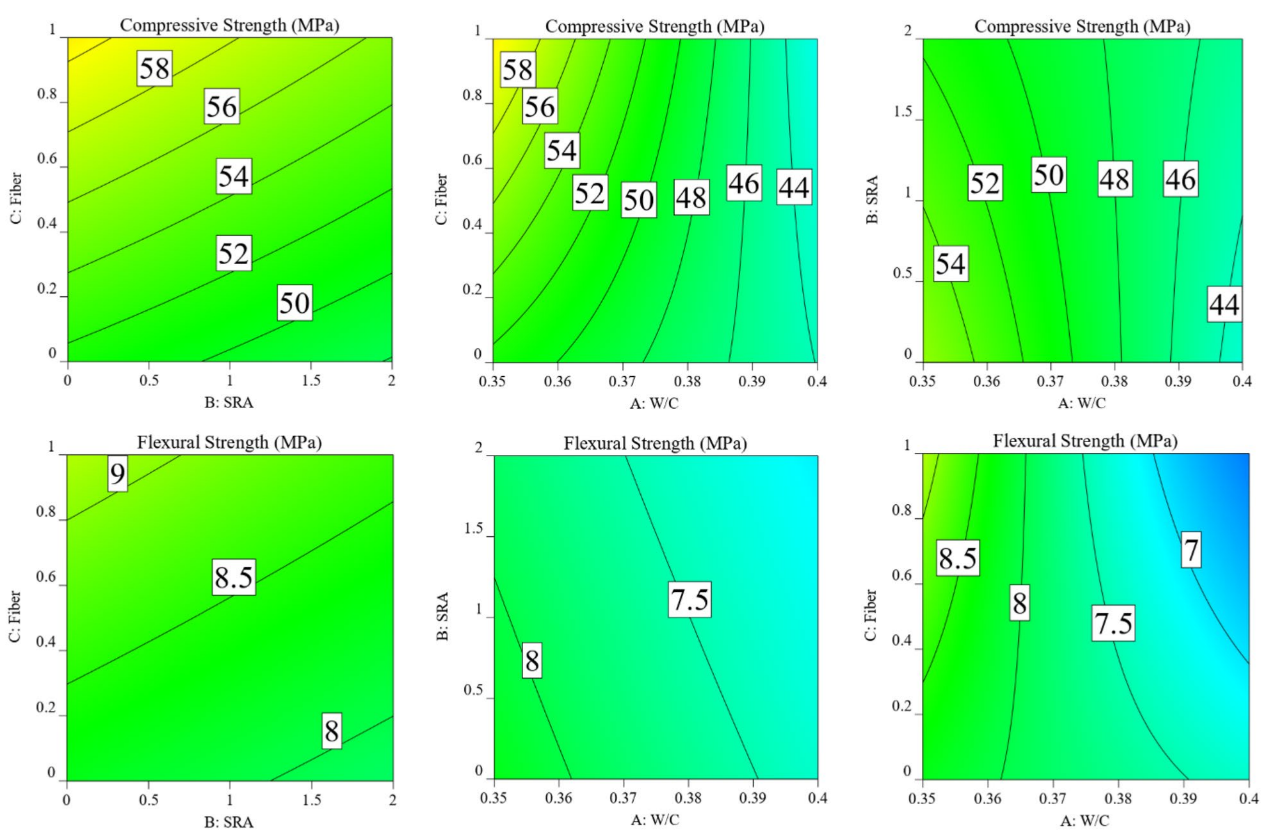

Fig. 2 RSM plots for compressive (top) and flexural (bottom) strength results

Table 10 Results of electrical resistance of all mix compositions

Concrete type	Age		
	7 days	28 days	90 days
OPC 0.35	13.67	16.75	23.33
SRA 0.35	11.67	15.17	22.76
FIBER 0.35	14.17	18.77	25.77
SRA & FIBER 0.35	13.83	17.5	24.17
OPC 0.4	10.62	12.92	17
SRA 0.4	7.63	9.32	13
FIBER 0.4	9.77	12.33	16.42
SRA & FIBER 0.4	11.17	13.83	18.33

polypropylene fiber had a negligible effect on flexural strength based on RSM plots. For example, there is no significant difference between the concrete with W/C of 0.38 and polypropylene fiber of 0.5%, and concrete with W/C of 0.38 and polypropylene fiber of 1% based on RSM plots on flexural strength values.

3.3 Electrical Resistance

Table 10 represents the results of electrical resistance. The reduction of the water–cement ratio improves the electrical resistance of concrete by up to 50%. In addition, when SRA is used in concrete, electrical resistance is reduced by around 20%. It could be due to retardation in hydration of cement (Chen et al., 2020; Deboodt et al., 2016) and increasing the ions' dosages in concrete (Zuo et al., 2019).

Electrical resistance was decreased using fibers in concrete with $w/c = 0.4$. In these FRCs samples, the porosity of concrete increased, and concrete homogeneity was decreased (Afroughsabet & Ozbakkaloglu, 2015). However, if the concrete homogeneity was increased, it may increase the electrical resistance because polypropylene fibers are non-conductive and reduce the conductivity of pores of capillary tubes (Eren & Marar, 2010; Ramezanianpour et al., 2013).

Results of the electrical resistance have been imported into Design-Expert software for analyzing data. Table 11 shows the output of using the ANOVA method on Design-Expert. Because of passing model adequacy checking, power transformation with lambda of − 0.15 was used. All effects and their interaction except the interaction of SRA & W/C were significant on transformed electrical resistance ($\alpha = 0.05$).

The RSM plots for electrical resistance results are represented in Fig. 3. In addition, polypropylene fiber had no significant effect on electrical resistance. As it can be seen, there is no difference between different percentages of fiber to electrical resistance at constant W/C. The results of the statistical analysis confirmed the previous arguments.

3.4 Free Shrinkage

The effect of using polypropylene fiber and SRA on the free shrinkage of concrete is shown in Fig. 4. The higher water–cement ratio of concrete increased the length change of concrete samples in this study. It might be that higher W/C caused increasing porosity of concrete, increasing transition zone and cement paste, and decreasing the volume of aggregate. Furthermore, SRA had mainly reduced concrete free shrinkage

Table 11 ANOVA for selected factorial model: electrical resistance

Source	Sum of squares	*df*	Mean square	*F*-value	*p*-value	
Block	0.0362	2	0.0181			
Model	0.0323	7	0.0046	215.93	< 0.0001	Significant
A-W/C	0.0230	1	0.0230	1076.25	< 0.0001	
B-SRA	0.0014	1	0.0014	63.59	< 0.0001	
C-Fiber	0.0032	1	0.0032	150.89	< 0.0001	
AB	**0.0000**	**1**	**0.0000**	**1.62**	**0.2085**	
AC	0.0002	1	0.0002	8.66	0.0046	
BC	0.0027	1	0.0027	125.71	< 0.0001	
ABC	0.0018	1	0.0018	84.80	< 0.0001	
Residual	0.0013	62	0.0000			
Lack of fit	0.0004	14	0.0000	1.43	0.1780	Not significant
Pure error	0.0009	48	0.0000			
Cor total	0.0698	71				
R^2	0.9606	**Adjusted R^2**	0.9561		**Predicted R^2**	0.9469

The values displayed in bold represent the non-significant parameters in the model

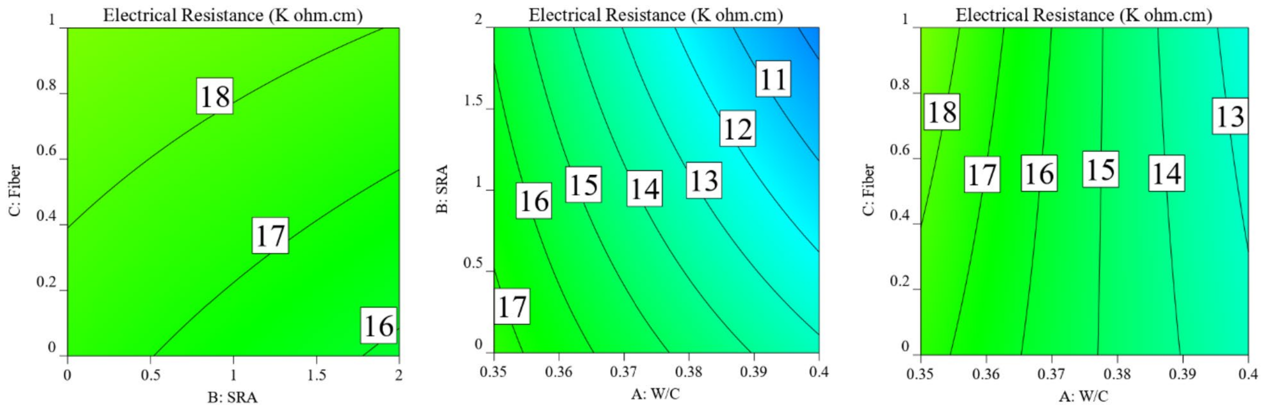

Fig. 3 RSM plots for electrical resistance results

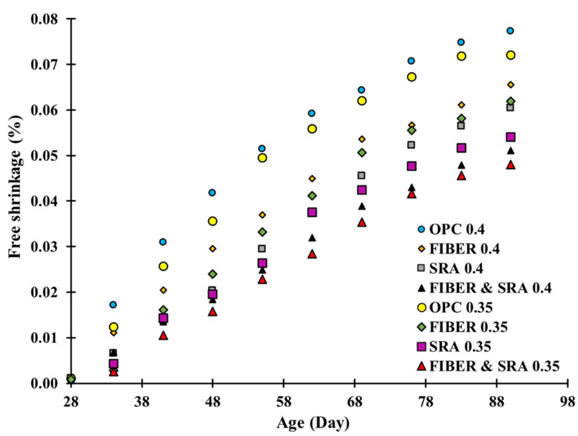

Fig. 4 Results of free shrinkage of all concrete mixtures

by about 10% at W/C of 0.4 and a 15% at W/C of 0.35. It was noted that using SRA had more effect on early age free shrinkage. Evaporation rate, the capillary tension of water, the initial temperature of concrete, and surface tension were reduced using SRA in concrete (Lura et al., 2007; Mehta & Monteiro, 2017; Mora-Ruacho et al., 2009; Rosen & Kunjappu, 2012; Wehbe & Ghahremaninezhad, 2017). Using fibers had a similar effect on length changes of concrete and caused about 15–50% reduction of free shrinkage on FRCs over OPC. It might be because of interlocking aggregates and fibers and absorbing cement paste on the surface of fibers that prevent the free movement of concrete components (Hsie et al., 2008; Olaoye et al., 2013).

Results of the free shrinkage have been imported into Design-Expert software. Table 12 shows the output of using the ANOVA method on Design-Expert. Because of passing model adequacy checking, power transformation with lambda of 0.35 and constant of 0.005 was used. All effects and interactions were significant on transformed free shrinkage ($\alpha = 0.05$).

The RSM plots for free shrinkage results are presented in Fig. 5. Based on contour plots, W/C had no significant effect on reduction of free shrinkage on fiber-reinforced concrete. As it is represented in Fig. 5,

Table 12 ANOVA for selected factorial model: free shrinkage

Source	Sum of squares	*df*	Mean square	*F*-value	*p*-value	
Block	0.4138	9	0.0460			
Model	0.0340	6	0.0057	54.71	< 0.0001	Significant
A-W/C	0.0012	1	0.0012	11.44	0.0012	
B-SRA	0.0142	1	0.0142	136.56	< 0.0001	
C-Fiber	0.0156	1	0.0156	150.73	< 0.0001	
AB	0.0020	1	0.0020	18.90	< 0.0001	
AC	0.0004	1	0.0004	3.89	0.0528	
BC	0.0007	1	0.0007	6.75	0.0116	
Residual	0.0066	64	0.0001			
Cor total	0.4544	209				
R^2	0.8368	**Adjusted R^2**	0.8216		**Predicted R^2**	0.7451

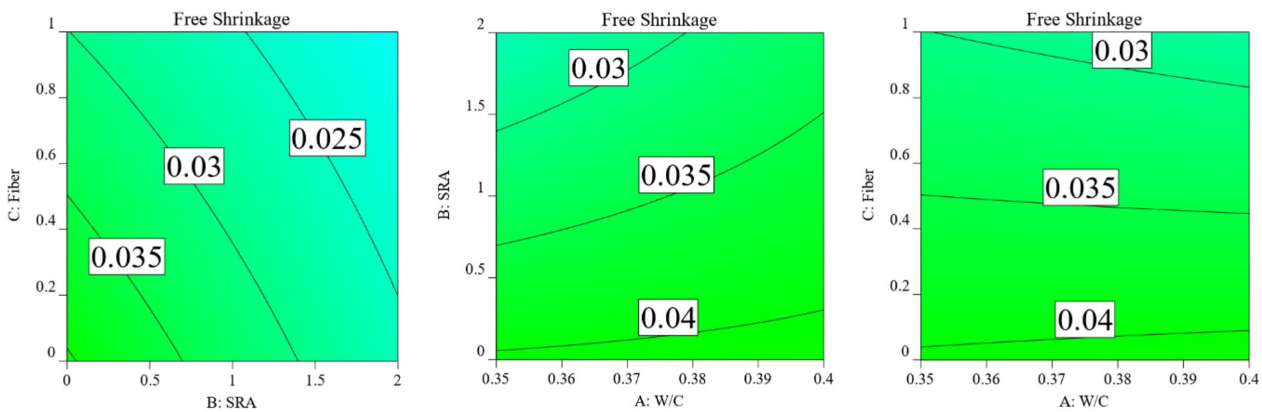

Fig. 5 RSM plots for free shrinkage results

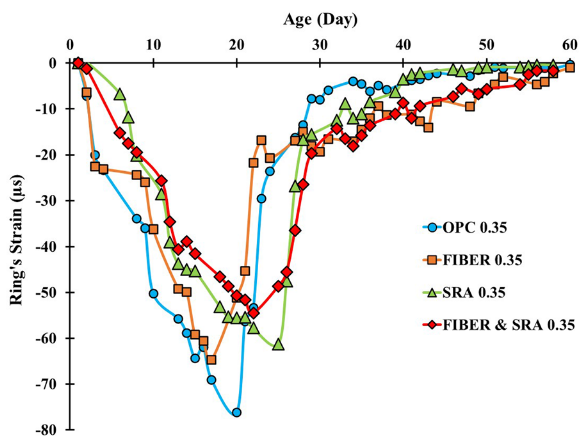

Fig. 6 Results of measuring strain of ring test

Fig. 7 Image of OPC specimen at the age of 60 days for evaluating crack width

SRA could reduce free shrinkage and be helpful in controlling that. In addition, W/C caused a reduction in free shrinkage on concrete containing SRA. So, for achieving the constant free shrinkage, the amount of SRA can be reduced by decreasing W/C.

3.5 Restrained Shrinkage

This test was carried out for concrete with $W/C=0.35$ due to experimental restrictions. Fig. 6 depicts the strain of steel rings for mixes. It shows that using SRA improved the behavior of concrete on restrained shrinkage. Using SRA delayed the time of first crack for about a week and reduced the magnitude of strain by about 20%. Improving the restrained shrinkage behavior of concrete might be happened because evaporation rate, the capillary tension of water, the initial temperature of concrete, and surface tension were reduced using SRA in concrete (Lura et al., 2007; Mehta & Monteiro, 2017; Mora-Ruacho et al., 2009; Rosen & Kunjappu, 2012; Wehbe & Ghahremaninezhad, 2017). Also, using SRA reduced the early age temperature of concrete and could delay the age of the first crack (Yuan et al., 2018). Using fibers had a negligible effect on the age of first cracks (reduction in the age of crack by about 1–2 days).

Furthermore, the magnitude of measured strain was reduced about 15% using polypropylene fiber. There are no chemical reactions between polypropylene fibers and other parts of concrete; also fibers had no significant change in the microstructure of concrete (Ramezanianpour et al., 2013). In the other words, fibers are used in concrete to bridge both sides of the crack and prevent crack development (Caggiano et al., 2016; Ramezanianpour et al., 2013). Nevertheless, reducing the restrained shrinkage might be due to interlock aggregates and fibers and absorbing cement paste on the surface to prevent the free movement of concrete components (Hsie et al., 2008; Olaoye et al., 2013).

In addition, the crack width of all ring specimens was measured by taking photos at different ages and using AutoCAD. To determine the crack width, the photos

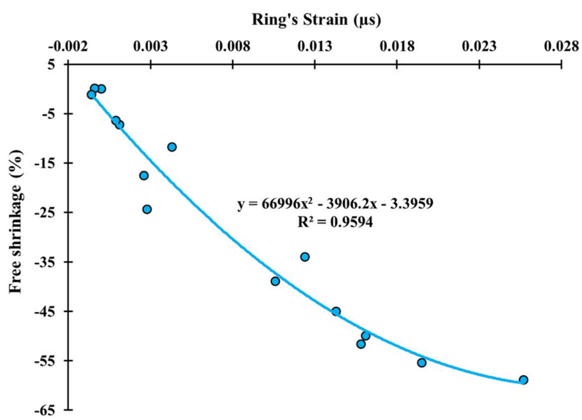

Fig. 8 The relationship between the results of free and restrained shrinkage

were first uploaded to the AutoCAD application. It is worth noting that all of the photos were taken from the same distance and angle. The photos were then scaled to their true dimensions, and finally, the width of the cracks was determined using the AutoCAD dimensions toolbar. Also, the value of crack width determined using this method and evaluated using a crack detection microscope were compared at certain ages. It was observed that this method had more than 98% accuracy in determining the crack width. Fig. 7 shows one of these pictures taken in this experiment. The results show that polypropylene fibers and SRA reduced crack width by about 35% and 45%, respectively. It seems that this is because of bridging both sides of cracks using polypropylene fibers (Caggiano et al., 2016; Ramezanianpour et al., 2013). Moreover, reduction in the evaporation rate, the capillary tension of water, the initial temperature of concrete, and surface tension are effects of using SRA which reduces the crack width (Lura et al., 2007; Mehta & Monteiro, 2017; Mora-Ruacho et al., 2009; Rosen & Kunjappu, 2012; Wehbe & Ghahremaninezhad, 2017).

3.6 Relationship Between Free and Restrained Shrinkage

Results of free and restrained shrinkage of all specimens were collected at the same age, as shown in Fig. 8. It was done because of the ring test's restrictions (special molds, warring about sensitivity and accuracy of using data logger) and the simplicity of the free shrinkage test as compared to the ring test. Using this fitting formula or the graph extended, it is possible to estimate the value of restrained shrinkage using the value of free shrinkage at the same age. It helps in cases where the restrained test is not possible to be performed. Fig. 8 represents a relationship between free and restrained shrinkage.

It shows that the relationship was independent of the type of concretes. As the data of all types of concrete mixtures were used for evaluating the relationship between both types of shrinkage.

3.7 Design of Concrete Pavement Slab

In this section, the effect of polypropylene fiber, SRA, and a combination of them on the length and thickness of concrete pavement slab were investigated. Notably, mixed composition of the Tehran-Shomal freeway (with a W/C of 0.35) was performed in this section because one of the essential goals of this study was to reduce thickness and increase the length of slabs. Also, the result of restrained shrinkage was measured just for mixed compositions with a W/C of 0.35.

Elastic modulus and flexural strength are two critical mechanical properties of concrete that affect the evaluation of concrete pavement slab thickness. Elastic modulus can be evaluated by compressive strength by Eq. (1) (Design et al., 2017).

$$E_c = 4770\sqrt{f_c}, \tag{1}$$

where in E_c and f_c are elastic moduli and compressive strength at 28 days in terms of MPa, respectively (Design et al., 2017). In addition, the modulus of rupture (flexural strength) can be measured by a flexural strength experiment or evaluated by compressive strength (Design et al., 2017). Equation (2) was used to calculate the thickness of the concrete pavement slab based on AASHTO 1993 and Report No.731 of the Iranian manual (Design et al., 2017; Officials, 1993).

$$\begin{aligned} Log\,(W_{18}) = {} & Z_r \times S_0 + 7.35 \times Log(D+1) \\ & -0.06 + \frac{Log\left[\frac{\Delta PSI_T}{4.5-1.5}\right]}{1+\frac{1.624\times 10^7}{(D+1)^{8.46}}} \\ & +(4.22-0.32P_t) \\ & \times Log\left[\frac{S'_C \times C_d \times (D^{0.75}-1.132)}{215.63 \times J \times \left[D^{0.75} - \frac{18.42}{(\frac{E_c}{K})^{0.25}}\right]}\right], \end{aligned} \tag{2}$$

wherein the definition and value of each parameter are described in Table 13.

So, the concrete slab thickness for each mix composition can be calculated using Solver plugin on excel software. The value of compressive and flexural strength, elastic modulus, and designed slab thickness are represented in Table 14. As it can be seen, there is no significant change in slab thickness.

Table 13 Definition and value of each parameter used in Eq. (2)

Parameters	Description	Value
W18	Predicted number of 80 KN (18,000 lb) ESALs	32,800,000
Z_R	Standard normal deviate	− 1.645
S_o	Combined standard error of the traffic prediction and performance prediction	0.35
D	Slab thickness (in.)	Design output
P_t	Terminal serviceability index	2.5
ΔPSI	Difference between the initial design serviceability index, p_o, and the design terminal serviceability index, p_t	2
S_c^t	Modulus of rupture of PCC (flexural strength) (psi)	Identified based on concrete type
C_d	Drainage coefficient	1
J	Load transfer coefficient (value depends upon the load transfer efficiency)	2.8
E_c	Elastic modulus of PCC (psi)	Identified based on concrete type
k	Modulus of subgrade reaction (pci)	350

Table 14 Results of concrete pavement design for evaluating slab thickness

Concrete type	F_c (MPa)	E_c (MPa)	S_c (MPa)	D (mm)
OPC 0.35	53.58	34,915.62	8.36	204
SRA 0.35	51.34	34,177.97	7.65	215
FIBER 0.35	63.74	38,082.41	8.6	202
SRA & FIBER 0.35	57.24	36,088.45	9.01	196

Table 15 Results of concrete slab length based on concrete stress due to friction

Concrete type	σ_c or S_c (MPa)	f_a	γ_c (kg/m^3)	L (m)
OPC 0.35	8.36	1.8	2372	399
SRA 0.35	7.65	1.8	2363	366
FIBER 0.35	8.6	1.8	2375	410
SRA & FIBER 0.35	9.01	1.8	2380	428

To evaluate the effect of fiber and SRA on the slab length, Eq. (3) was used (Huang, 2004).

$$\sigma_c = \frac{\gamma_c \times L \times f_a}{2}, \tag{3}$$

In which σ_c is the flexural strength of concrete, γ_c the unit weight of the concrete, L the slab length, and f_a the average coefficient of friction between slab and subgrade, usually taken as 1.5 (friction is independent of the slab thickness) (Huang, 2004).

So, the concrete slab length (joint spacing) for each mix composition can be calculated based on concrete stress due to friction. The average coefficient of friction between slab and stabilized based on the Tehran-Shomal freeway was considered to be 1.8 (Table 15).

As expected, the value of slab length of concrete pavement based on concrete stress due to friction was not dictated (Huang, 2004).

In addition, the joint spacing of concrete slab depends more on concrete shrinkage characteristics than concrete stress due to friction (Huang, 2004). To evaluate concrete slab length based on the shrinkage characteristics, Eq. (4) was suggested by Darter and Barenberg (1977).

$$\Delta L = C \times L \times (\alpha_t \times \Delta T + \varepsilon), \tag{4}$$

in which ΔL is the joint opening caused by temperature change and drying shrinkage of concrete; ε the coefficient of drying shrinkage concrete (free shrinkage); α_t the concrete thermal expansion coefficient, generally between 5×10^{-6}/°F and 6×10^{-6}/°F (9×10^{-6}/°C and 10.8×10^{-6}/°C); ΔT the temperature range, which is the temperature at placement minus the lowest mean

Table 16 Results of concrete slab length based on the shrinkage characteristics

Concrete type	ΔL (m)	α_t (1/°C)	ΔT (°C)	C	ε	L (m)
OPC 0.35	0.004	10.8×10^{6}	40	0.65	7.7×10^{4}	5.12
SRA 0.35	0.004	10.8×10^{6}	40	0.65	5.4×10^{4}	6.33
FIBER 0.35	0.004	10.8×10^{6}	40	0.65	6.29×10^{4}	5.80
SRA & FIBER 0.35	0.004	10.8×10^{6}	40	0.65	4.8×10^{4}	6.75

Table 17 Initial cost of each mix composition (Tomans/m^3)

Concrete type	Initial cost (Tomans/m^3)
OPC 0.35	550,000
SRA 0.35	1,000,000
FIBER 0.35	900,000
SRA & FIBER 0.35	1,250,000

monthly temperature; L the joint spacing or slab length; and C the adjustment factor due to slab-subbase friction that is 0.8 for granular subbase and 0.65 for the stabilized base (Huang, 2004).

The slab length was calculated based on the Tehran-Shomal concrete pavement design. The value of joint opening was considered 4 mm (current slab length of Tehran-Shomal freeway is 5 m, and by back-calculation and use results of this study, the value of joint opening identified 4 mm). Also, the value of the adjustment factor (C) was 0.65 because the base layer of the Tehran-Shomal freeway is a stabilized base. In addition, ΔT and coefficient of thermal expansion (α_t) were considered 40 °C and 10.8×10^{-6}/°C, respectively. In the end, the amount of free shrinkage for each mix composition was determined from Sect. 3.4. The concrete slab length (joint spacing) for each mix composition based on shrinkage characteristics was calculated. Table 16 displays the results of slab length that is calculated based on Eq. (4).

As can be seen, using SRA and fiber had a positive effect on slab length and caused an increase of about 25% and 15% in the length of the slab, respectively. Using polypropylene fiber and SRA increases the length of concrete slabs by reducing the rate of cracking and the coefficient of drying shrinkage of concrete. It means that due to reducing the value of the coefficient of drying shrinkage, the total strain caused by the environmental condition (summation of the strain caused by temperature changes and drying shrinkage) decreased. So for the same value of joint opening, larger concrete slab could be produced using SRA and polypropylene fiber while maintaining a total strain similar to that in the control mixture. This issue is important from two perspectives: first of all, by reducing the number of dowel bars used and thus requiring less labor, the overall cost of pavement construction is decreased. Second, an acceleration in the implementation process is achieved so that the desired route may become operation sooner. In addition, SRA and polypropylene fiber caused an improvement in the crack generation of concrete. This issue may not have a direct impact on determining the length and thickness of the concrete slabs, but it directly influences the lifetime of concrete pavement slabs. This is because the crack will generate at a lower rate in concrete slabs and the concrete distresses will be significantly reduced.

Table 18 Initial cost of each mix composition to use in Tehran-Shomal freeway (Tomans/m^2)

Concrete type	Initial cost (Tomans/m^2)
OPC 0.35	255,000
SRA 0.35	335,000
FIBER 0.35	305,000
SRA & FIBER 0.35	360,000

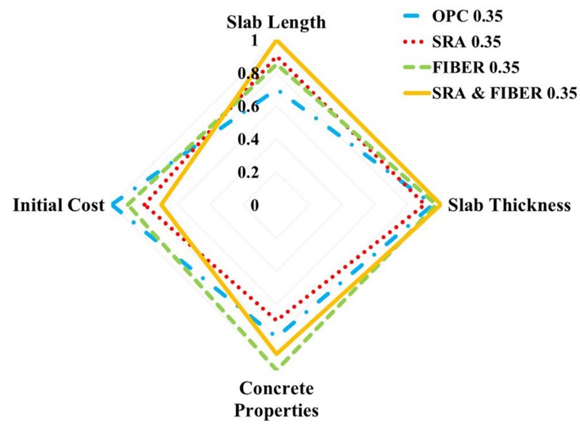

Fig. 9 The effect of using SRA and polypropylene fiber on concrete pavement properties

3.8 Cost Analysis and Choose the Best Alternative

The initial cost of each mix composition is performed in Table 17 (Tomans/m^3). The initial cost of each mix composition includes the prices of cement, sand, gravel, superplasticizer, SRA, and polypropylene fiber.

As it is represented, the initial cost of the mix increased using SRA and fiber. However, these admixtures reduced the implementation costs (by increasing the slab length and rate of execution and decreasing slab thickness, required dowel bar, and labor). So, the initial costs of each mix composition utilized in the Tehran-Shomal freeway were calculated per square meter and displayed in Table 18.

By the way, Fig. 9 displays the effect of SRA and polypropylene fiber on the results of concrete pavement design, concrete properties, and initial cost. As it can be seen, the concrete slab containing SRA and fiber had more length and less thickness than the others, but it was a high price. Also, the plain concrete slab was the best solution if only the economic aspects were considered. Finally, it seemed fiber-reinforced concrete had a more desirable option after considering all the parameters. Because use of fiber in concrete pavement improved the concrete properties and increased the slab length by about 15% without any significant change in slab thickness; in contrast, it only increased initial costs of production, construction, and execution by about 20%.

4 Summery and Conclusion

This research investigated the length of concrete pavement slab containing shrinkage reducing admixture and polypropylene fiber. The following conclusions can be drawn based on the observed results:

1. The addition of SRA has no influence on the fresh properties of concrete. Also, the electrical resistance of concrete was reduced as well as mechanical properties using SRA due to retardation of cement hydration. Also, using fiber, the mechanical properties and electrical resistance of concrete were improved; however, the workability of concrete decreased.
2. Free and restrained shrinkage of concrete was reduced by about 15% and 20% using fiber and SRA, respectively. In addition, the age of concrete at first crack was increased by 8 days, and the crack width decreased by more than 40%. There was a negligible change in the age of first crack when fiber was used. In addition, it decreased the crack width by about 35% through bridging the sides of the crack.
3. Statistical analysis on the experimental results represented that W/C, SRA, and fiber were significant parameters on all objective functions. It also represented that by considering lower W/C, some of the advantages of using SRA and fiber could be reached. Furthermore, the results clarified that a fiber-reinforced concrete with a W/C of 0.35 had the best performance considering all aspects.
4. Investigation on the effect of SRA and fiber on concrete pavement slab length and thickness demonstrated that using these materials in concrete mix composition, the concrete slab length can be increased up to 20% without any significant change in the concrete slab thickness.

Overall, it was shown that using polypropylene fiber and SRA reduced the free and restrained shrinkage of concrete, controlled the crack width, and had no serious negative effect on the properties of concrete. In addition, the length of concrete slabs could be increased using SRA and polypropylene fiber. Improving the durability and performance of concrete pavements during their lifetime and increasing the rate of construction for concrete pavements are some advantages of using these materials in real projects, such as the Tehran-Shomal freeway.

Acknowledgements
This article was written in collaboration with Professor Ali Akbar Ramezanianpour (1951-2021), the late Professor of Civil Engineering and Environmental Engineering, Amirkabir University of Technology. May his soul be happy and his memory is cherished. Also, I am really thankful to Sirjan Nano Yarn and Granule Company for covering a portion of the study expenses.

Author contributions
MG collected and analyzed experimental data regarding the concrete properties and evaluate the slab length and thickness. FM helped analyze pavement results and AMR helped analyze concrete properties and investigate other sections. All authors read and approved the final manuscript.

Funding
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Availability of data and materials
All data, models, and code generated or used during the study appear in the submitted article.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 22 April 2022 Accepted: 6 October 2023
Published online: 06 February 2024

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