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Effects of steel fiber reinforcement on surface wear resistance of self-compacting repair mortars

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Abstract

Self-compacting repair mortars (SCRM), as new technology products, are especially preferred for the rehabilitation and repair of reinforced concrete structures. The self-compactability of repair mortars may bring considerable advantages at narrow mould systems. However, due to the high powder content and absence of coarse aggregate, plain SCRMs are susceptible to surface abrasion, especially in case of repair of surfaces under high rates of abrasion (floors, slabs). Steel fiber reinforcement can be an excellent solution for the abrasion resistance problem of SCRMs. However, the optimum amount of fiber reinforcement to sustain self-compactability should be predetermined. In this study, the optimum superplasticizer dosage and the maximum possible amount of fiber addition, which maintain the self-compactability and stability, was determined for mortars incorporating steel fibers. In addition, the mechanical performance and abrasion resistance of SCRMs prepared by using these fibers were determined. It was concluded that steel fibers can have rheological and mechanical synergistic effects, and that optimised fiber – superplasticizer dosage combinations can better improve the wear resistance while maintaining adequate flow properties for FR-SCRM.

Keywords: Self-compacting repair mortars; Short-fiber composites; Wear; Strength

1. Introduction

The use of fibers – depending on the fiber type – may considerably increase the toughness, energy absorption capacity, reduce cracking, improve the impact resistance and durability of cement based materials [1–5]. The concrete reinforcing fibers are usually composed of metals, polymers and others. Among the polymer fibers, the polypropylene fibers enjoy popularity and the nylon fibers show a rising acceptance to combat with plastic and drying shrinkage cracking [6–8]. On the other hand, steel fiber added concrete or mortar has been used to increase for the toughness, energy absorption capacity or the impact resistance in applications like: slabs and floors, shell domes, rock slope stabilisation, refractory linings, composite metal decks, aqueduct rehabilitations, seismic retrofitting, repair and rehabilitation of structures, fire protection coatings, concrete pipes etc. [9–13].

The application of fibers in concrete was regarded as very difficult in the past, due to insufficient workability of fiber-reinforced mixtures. The development of self-compactability for cementitious systems has proven to offer significant improvements in application of fibers in concrete. Fibers can have rheological and mechanical synergistic effects, and that optimised fiber combinations can better increase mechanical performance while maintaining adequate flow properties for fiber-reinforced self-compacting mortar [13]. Self-compacting repair mortars (SCRM), as new technology products, are especially preferred for the rehabilitation and repair of reinforced concrete structures [14]. The repair mortar applied to concrete is usually hard to consolidate, and in most cases vibration is not possible. From this point of view, the self-compactability of repair mortars may bring considerable advantages at narrow

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mould systems [15]. With the development of new generation plasticizers, to obtain high filling rates is possible even for complex moulding systems [16]. However, due to the high powder content and absence of coarse aggregate, SCRMs are susceptible to surface abrasion, especially in repair of surfaces with high abrasion impact (in particular slabs and floors). The use of fibers may provide a way of improving the abrasion resistance of SCRM depending on the type and amount of fiber used. In the absence of self-compactability the success of fiber reinforced repair mortars depends on the compaction degree supplied at application site. In this study, the performances of SCRMs incorporating steel fibers were investigated. First, the optimum admixture dosage and maximum possible fiber amounts were determined for the selected steel fibers to obtain stable and self-compactable repair mortars. Second, the mechanical performance and abrasion resistance of SCRMs reinforced by the maximum possible amount of fibers were compared.

2. Experimental study

2.1. Materials

An ordinary Type-I Portland cement (CEM I 42.5N) was used in all compositions. In order to enhance the paste content, finely grounded limestone filler from Ozture Mugla Factory and a C-type fly ash in conformity with ASTM C 618 [17] from Soma B power plant were employed. The chemical composition and the physical properties of cement, fly ash and limestone filler are given in Table 1. Local well-graded natural sand with a maximum size of 4 mm was used. The superplasticizer (SP) was a "polycarboxylic-acid" type; commercially branded as HS100 "Smart flow" produced by Konsan Science and Technology Production Corporation, Izmir, Turkey. It is an ASTM C 494 [18] F-type high-range water reducer. The solid content, pH and specific gravity of admixture were 35.7%, 6.5%, and 1.11%, respectively. Short steel of 5 mm length and aspect ratio of 30 were employed. The density, modulus of elasticity and tensile strength of fibers were 7.80 g/cm^3, 210 GPa and 1100 MPa, respectively.

Table 1
The chemical composition and some of the physical properties of cement, fly ash and limestone filler

Basic compounds (%)	Cement	Fly ash	Limestone filler
CaO	63.70	26.96	52.35
SiO_2	19.68	42.14	0.45
Al_2O_3	5.75	19.38	0.33
Fe_2O_3	3.00	4.64	0.14
MgO	0.90	1.78	1.05
Na_2O	0.20	–	0.06
K_2O	0.83	1.13	0.02
SO_3	2.78	2.43	–
Cl	0.01	0.001	–
Loss on ignition	2.84	1.34	42.50
Free CaO	1.55	4.34	–
Insoluble residue	0.70	–	0.20
Specific surface (m^2/kg)	340	290	538
Specific gravity	3.14	2.20	2.65

2.2. Determination of maximum possible fiber amount at optimum admixture dosage to obtain a self-compactable and stable mortar

The water/binder and sand/binder ratios of SCRMs were kept constant to 0.50 and 2.25, respectively. The powder mixture compositions of all SCRMs were composed of 70% cement, 25% fly ash and 5% limestone filler, respectively. The ternary mixture proportion of powder composition was determined in a former study [19].

The amount of mortar combination is adjusted to 1.2 L per batch. A Hobart mixer was used. It is important to achieve a uniform cement, filler and admixture combination in exactly the same way every time to reach a satisfactory repeatability. For this reason, the following mixing sequence was used for all mixtures:

1. Cement, filler combinations and sand are dry mixed for 3 min.
2. The water and superplasticizer are mixed in a flask and poured slowly into the bowl of mixer while mixing. Finally fibers are added to the mix. The mortar is mixed for 3 min at low rotation speed and 2 min at high rotation speed.
3. The mixer is stopped and the mortar is poured into the V-funnel (1 L capacity) in conformity with EFNARC [20] standards (Fig. 1). The V-funnel times were measured for each mixture at different fiber amounts and admixture dosages. Note that due to instability or inadequate flowability of mortars, the V-funnel values of some mixtures could not be measured.

For stable and self-compactable flowability, the upper and lower admixture dosages for each fiber amount were determined by using the V-funnel apparatus. The filling ability of mortars with long V-funnel times (usually above 30 s) was poor. For this reason, first of all, the lower limit of admixture dosage to obtain a V-funnel time of approximately 30 s was determined. Then, the admixture dosage was increased with an interval of 0.2% (by weight of

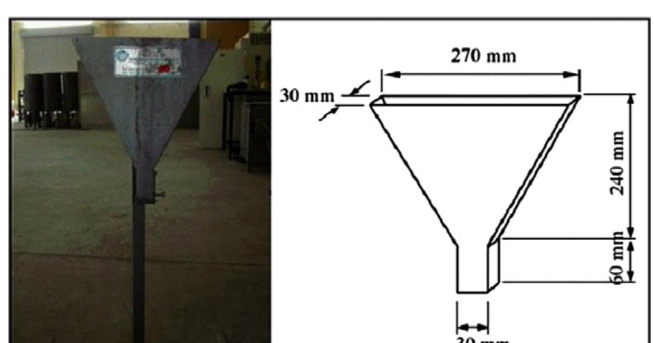

Fig. 1. V-funnel for self-compacting mortars (1 L capacity).

cementitious material) for each fiber amount and the self-compactability and stability of the mortar was observed. The upper limit of admixture dosage that maintains the stability of mortar was also determined for each fiber amount. Upper limit was determined by static segregation check test with the same funnel. In this test, sample was poured into the funnel and waited for a while to settle. If the stability of mortar is poor, both fine aggregate and steel fiber settlement occurs and test results with plugging. The optimisation methodology of admixture dosage of SCRMs as a function of fiber amount-V-funnel time relationship for steel fibers is illustrated in Fig. 2. It was observed that, at different fiber amounts even at variable admixture dosages it was not possible to restrict the V-funnel time into limited values for a self-compactable and stable mortar mixture. For example, at fiber content of 78 kg/m^3, the V-funnel time of 18 s is enough to obtain a stable SCRM, however, the same V-funnel time is not enough to obtain self-compactability at fiber content of 195 kg/m^3. Note that, this observation is valid for the same mortar cementitious material/fine aggregate proportion and paste content. For steel fibers, the highest fiber amount and the optimum admixture dosage for this mortar mixture was 156 kg/m^3 and 1% by weight of cementitious material to obtain a self-compactability and stability at the same time respectively. Even at this high steel fiber content, no clumping was occurred. This can be attributed to moderate viscosity and high flowability of SCRMs supported by admixture and high paste content. If the admixture dosage of mortar (with the fiber amount of 156 kg/m^3) increased higher than 1.2%, mixture tended to loss its stability and segregation occurred. On the other hand, if the admixture dosage was reduced to lower than 0.8%, the flowability of mortar was not enough and resulted with the plugging of V-funnel.

When the fiber amount increased to 195 kg/m^3 the self-compactability can not be maintained even the admixture dosage increased. Due to the insufficiency of the paste content, it was impossible to supply enough viscosity and passing ability at this excessive fiber content. The maximum possible fiber content was 156 kg/m^3 for steel fibers and

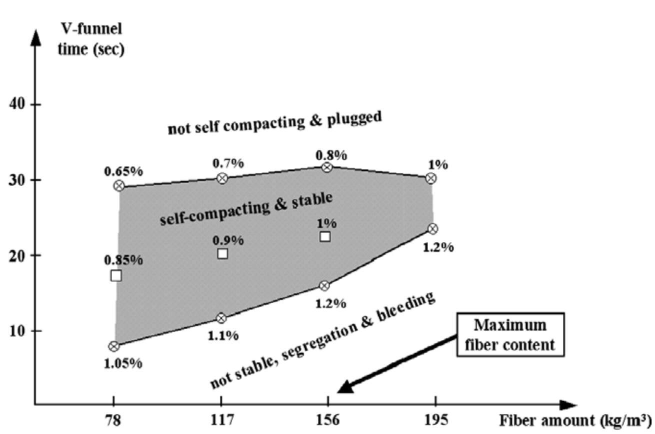

Fig. 2. Optimisation methodology of admixture dosage of SCRMs as a function of fiber amount-V-funnel time relationship for steel fibers.

can be regarded as fiber saturation amount for this SCRM mixture design. Note that, changing mixture proportions can increase the fiber saturation point. If the paste content is increased higher fiber contents may be reached without loss of self-compactability and stability.

2.3. Mechanical performance and abrasion resistance of selected SCRMs containing maximum possible fibers for self-compactability

Two SCRM mixtures one is plain and the other is containing steel fibers (maximum possible fiber amount for self-compactability) were prepared. The optimum admixture dosages of plain (0.8% by wt.) and SCRM (1.0% by wt.) mixtures were previously determined by using the V-funnel test (Section 2.2). The maximum possible fiber amount for self-compactability was 2% (by volume) or 156 kg/m^3.

The mini-slump flow test in conformity with EFNARC [20] standards is also conducted to verify the self-compactability of mortars (Fig. 3). In this test, the truncated cone mould is placed on a metal plate, filled with mortar and lifted vertically. The spread diameter of the mortar is measured in two perpendicular directions, and the mean is taken [21]. The initial diameter of the cone is 100 mm. The mini-slump flow values of SCRMs containing maximum possible fiber amount and optimum superplasticizer dosages were in the range of 240 ± 20 mm.

After the completion of mini slump tests, the SCRM mixtures were poured into prismatic moulds with $40 \times 40 \times 160$ mm and cubic moulds with $71 \times 71 \times 71$ mm dimensions without any compaction or vibration. Specimens were demoulded after 24 ± 2 h and kept in lime saturated water until the testing day.

Flexural and compressive strength tests were performed in conformity with ASTM C348 [22] and C349 [23] standards at 7 and 28 days after casting. Test results for flexural strength obtained from the average of three specimens and compressive strength obtained from the average of six broken pieces of specimens for each age are presented in Table 2.

Plain and fiber modified SCRMs with $71 \times 71 \times 71$ mm dimensions were subjected to abrasion test at 28 days after casting. Before testing, specimens were dried in an oven at 50 °C until reaching a constant gravity. Bohme test apparatus is used for the test (Fig. 4). Although this standard is highly recommended for the abrasion of natural stones, it can also be applied on concrete specimens as an alternative of ASTM C779 [24]. Many other researchers used this method and obtained reliable results [25,26]. In compliance with TS 699 [27], the abrasion system had a steel disc, which had a diameter of 750 mm and rotating speed of 30 ± 1 cycle/min, a counter and a lever, which could apply 300 ± 3N on the specimens. Abrasion test apparatus is shown in Fig. 4. In the test procedure, 20 ± 0.5 g of abrasion dust (corundum-crystalline Al_2O_3) was spread on the disc, the specimens were then placed, the load was applied

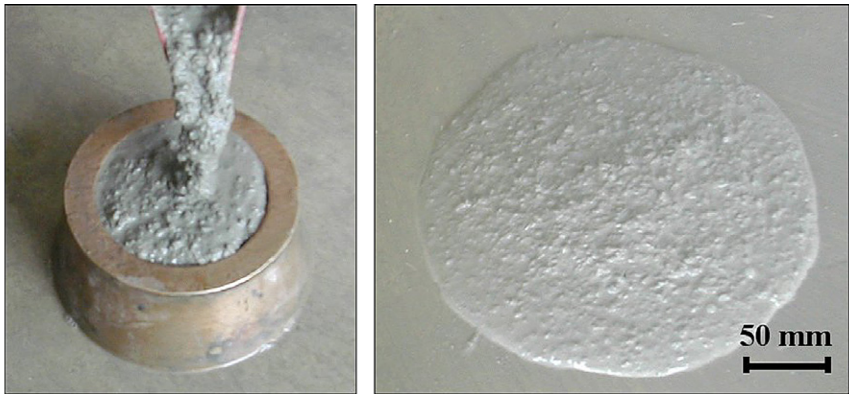

Fig. 3. The mini-slump flow testing of SCRM.

Table 2
Physical and mechanical test results

Notation	Abrasion loss[a] (% by wt.)	Flexural strength[a] (MPa)		Compressive strength[a] (MPa)	
	28 days	7 days	28 days	7 days	28 days
C	4.3 (1.4)	5.6 (2.7)	9.6 (0.6)	25.5 (1.7)	48.2 (0.8)
St	2.5 (3.0)	5.6 (1.9)	11.4 (2.0)	25.4 (1.0)	55.2 (0.7)

[a] Coefficient of variation of test results (%) are presented in brackets.

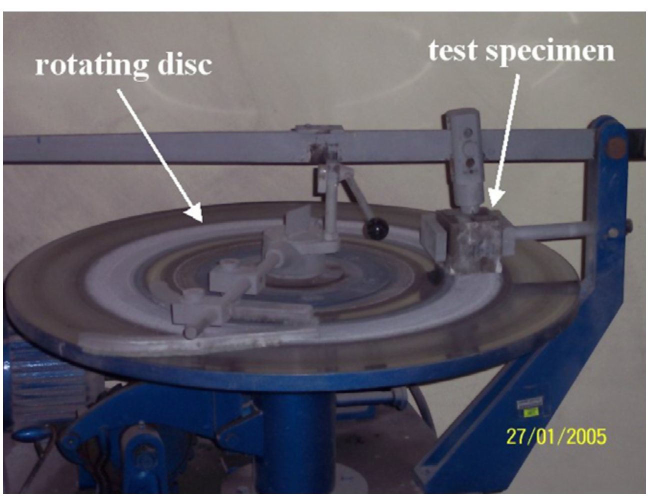

Fig. 4. Bohme test apparatus used for wear test.

to the specimen and the disc was rotated for 4 periods, while a period was equal to 22 cycles. After that, the surfaces of the disc and the sample were cleaned. The abovementioned procedure repeated for 5 periods (totally $5 \times 88 = 440$ cycles) by rotating the sample 90° in each period. The weight loss due to wear was measured, the average of three results are given in Table 2.

The coefficient of variation of results of flexural, compressive strength and abrasion resistance tests are presented in Table 2. The coefficients of variations were lower than 5%, which indicated that samples were quite homogeneous. This situation is attributed to the compaction free casting of samples. Even though they contain fibers, self-compactability eliminated the compaction related imperfections in fiber reinforced SCRM of mixtures, thus a better homogeneity is obtained. It can be concluded that, synergistic effects of fibers from the view point of mechanical performance and better homogeneity can be much pronounced if they are employed in stable SCRMs.

3. Results and discussion

The most important disadvantage of incorporating a fiber is the loss of workability thus, increasing the difficulty of casting. This situation mostly results with inadequate workability and high volumes of entrapped air in mortar, which causes strength loss and reduces the service life of material. However, it is possible to obtain high spread values by increasing plasticizer dosage up to some degree (depending on the paste amount stability can be maintained at higher admixture dosages). Even though fibers have a negative effect on workability, it is possible to obtain adequate workability with fibers in SCRMs. The self-compactability of fiber modified SCRMs bring a perfect filling ability and the amount of entrained air is minimized. Even though they contain high amounts of fibers, surface qualities of mortars are improved.

For conventional concrete, steel fiber dosages smaller than 1% (by volume) become ineffective and dosages beyond 2.5% (by volume) become also ineffective mainly due to the physical difficulties in providing a homogeneous distribution of the fibers within the concrete causing an appreciate drop in the compressive strength as compared to the plain concrete of the same class. However, the addition of steel fiber at 2% (by volume) caused no considerable compressive strength loss, which can be attributed to the better compaction and homogeneity of fiber distribution in steel fiber, reinforced SCRMs.

The 28 days flexural strength of steel fiber containing mix is 40% higher than control mix. However, the 7 days flexural strengths of all specimens were nearly the same. The above-mentioned later age improvement can be attributed to the enhancement of steel mortar interface related with frictional forces. Concerning the mechanical properties of conventional steel fiber reinforced mortar or concrete, there was usually no influence of steel fibers on the flexural or tensile strength, but mostly on ductility or toughness [28]. However, in steel fiber reinforced SCRMs, the steel fibers have a much higher influence on the mechanical properties, than in conventional fiber concrete. This is especially pronounced in the improved values of flexural strength. The improvements are directly related to the advanced properties in the fresh state. Therefore self-compactability and steel fiber reinforcement may trigger the mechanical performance of cementitious systems [28].

In this study, main purpose of using fibers was to improve the abrasion resistance of SCRMs. Steel fiber reinforced mix had a considerably improved abrasion resistance compared to plain mortars. The usage of steel fibers decreased the abrasion induced weight loss by 42%.

4. Summary and conclusions

In general, incorporation of steel fibers decreased the workability of fresh mortars up to some degree at constant water content and superplasticizer dosage. However, addition of superplasticizer depending on the type and amount of fiber may improve the workability and self-compactability can be obtained if mortar contains adequate paste to maintain stability.

The optimum superplasticizer dosage and the maximum possible amount of steel fiber addition, which maintain the self-compactability, and stability of SCRMs can be determined by using V-funnel test. However, no unique V-funnel time intervals can be pronounced for self compactability due to ternary effects of admixture dosage, fiber amount and paste content on stability and flowability of SCRMs. Admixture dosage of SCRMs as a function of fiber amount-V-funnel time relationship can be optimised by using the methodology described in this study.

The incorporation of steel fibers considerably improved both flexural and compressive strengths. This improvement may be attributed to enhanced compactability of the mix and compatibility of steel and mortar from the viewpoint of interfacial strength gain.

Steel fiber (156 kg/m^3) addition decreased weight loss due to abrasion by 42% and improved the 28 days flexural strength by 19%. The optimised fiber and superplasticizer dosage at a given paste content can have better physical and mechanical synergistic effects while maintaining adequate flow properties for FR-SCRM.

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