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Elaboration and characterization of fiber-reinforced self-consolidating repair mortar containing natural perlite powder

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Abstract. This research project aimed at evaluating experimentally the effect of natural perlite powder as an alternative supplementary cementing material (SCM) on the performance of fiber reinforced self-consolidating repair mortars (FR-SCRMs). For this purpose, four FR-SCRMs mixes incorporating 0%, 10%, 20%, and 30% of natural perlite powder as cement replacements were prepared. The evaluation was based on fresh (slump flow, flow time, and unit weight), hardened (air-dry unit weight, compressive and flexural strengths, dynamic modulus of elasticity), and durability (water absorption test) performances. The results reveal that structural repair mortars confronting the performance requirements of class R4 materials (European Standard EN 1504-3) could be designed using 10%, 20%, and 30% of perlite powder as cement substitutions. Bonding results between repair mortars containing perlite powder and old concrete substrate investigated by the slant shear test showed good interlocking justifying the effectiveness of these produced mortars.

Keywords: fiber reinforced self-consolidating repair mortar (FR-SCRM); flowability; mechanical properties; perlite powder; slant shear

1. Introduction

Cracks in concrete structures are inevitable. These cracks result usually from poorly concrete mix design, overloading, corrosion, exposure to high temperatures, shrinkage, etc. (Benjeddou *et al*. 2007, Jummat *et al*. 2006). The crack-induced problems can be overcome by incorporation of fiber in the cementitious matrices. Polypropylene fibers (PPF) is one of commonly used fibers in cementitious matrices, which can improve toughness properties and restrict plastic shrinkage cracks of mortar (Sanjuan *et al*. 1997). Smith and Atkinson (2010) found also that the inclusion of PPF in cementitious composites increased their resistance to spalling during fire.

However, the addition of non-well dispersed fiber can affect negatively the mortar workability,

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which is the key factor to obtain successful fiber-reinforced mortar for repair applications (Kurder *et al.* 2007). Highly flowable or self-consolidating mortars that can be placed without any external consolidation techniques can be interesting as a repair mortar, given it stability during casting and finishing. Nowadays, self-consolidating repair mortars ($SCRM_s$), as new technology products are especially preferred for the rehabilitation and repair of reinforced concrete structures (Courard *et al.* 2002). In addition to reducing labor time and noise, the SCRM technology can be also involved in filling narrow gaps between congested steel bars and coatings (Khayat and Morin 2002).

The main difference between $SCRM_s$ and ordinary mortar is the presence of a large amount of mineral admixtures (pozzolanic or inert fillers) in the former (Cyr *et al.* 2000). The common mineral admixtures that are likely used in $SCRM_s$ are fly ash, quarry dust powder, blast furnace slag, silica fume, and/or quartzite powder (Okamura and Ouchi 2003, Ferraris *et al.* 2000). Indeed, the mineral admixtures can be blended with cement or added separately during the mortar mixing (Erdoğan 1997). The use the mineral admixtures in $SCRM_s$ is not only to enhance flowability properties but also to improve strength and durability characteristics. The cement-based mixtures made with mineral admixtures as partial cement replacement are usually less expensive and eco-friendly. Unfortunately, the traditional mineral admixtures are not available in all areas and would be costly if transported. This gives the motivation to search for alternative local available materials that can be used as mineral admixtures for the production of SCRM.

Perlite is a glassy volcanic rock with a pearl-like luster, characterized by concentric onionskin fractures. Perlite has certain properties that are distinctly different from other volcanic glasses such as pumice, hydrated volcanic ash, and obsidian. Upon rapid heating to a suitable point in its softening range, the perlite expands creating large volume of bubbles, which are responsible for its low density (Ennis 2011). Perlite mines are easily accessible in the most areas of the world. It was reported that huge amounts of approximately 2530 K and 2680 K tons of perlite were produced in 2014 and 2015, respectively (Kimball 2016). In recent years, there was more research attention towards the valorization of natural perlite in various industrial applications, including concrete and mortar. Several studies have been carried out to determine the properties of the natural perlite powder and its use as construction material. For example, Aşik (2006) used the natural perlite as a lightweight aggregate in concrete to reduce the overall structure dead loads. Eser (2014) incorporated natural perlite aggregate in the production of high-performance lightweight concrete with 28-day compressive strength of up to 50 MPa. The ground perlite (perlite powder) can be considered as a potential mineral admixture with high pozzolanic activity for concrete or mortar, due to the amorphous structure and high SiO_2 and Al_2O_3 contents (Yu *et al.* 2003, Demirboga *et al.* 2001, Urhan 1987). Similar to the pozzolanic materials, blended cement with perlite powder may cause strength loss at early age compared with pure Portland cement, with improved strength at later age due to the pozzolanic reaction (Erdem *et al.* 2007). Yu *et al.* (2003) and Erdem *et al.* (2007) showed that perlite powder possess pozzolanic reactivity when used in cement matrix as Portland cement replacement by up to 30% substitution level. However, Turanli *et al.* (2005) reported that the replacement of cement with high levels of perlite powder tends to lower strength at early age compared to control. Uzal *et al.* (2007) reported that concrete mixture containing perlite powder exhibited low strength compared to control mixture at all ages up to 91 days. Also, Yu *et al*. (2003) studied the evolution of compressive strength of three mortar mixes containing 20%, 30%, and 40% of perlite powder at 3, 28, and 90 days. The 90-day compressive strength results showed increases of about 34%, 24%, and 8% compared to the control, respectively, which confirms the pozzolanic reactivity of perlite powder. In addition to strength gain at later age, the use of perlite powder in cementitious matrix provides high freeze-thaw resistance and fire protection capability (Mo and Fournier 2007).

The main objective of the current study is to evaluate the feasibility of producing fiber-reinforced self-consolidating repair mortars (FR-SCRM$_s$) using local natural perlite powder and to evaluate the overall performance of the FR-SCRM$_s$. Three FR-SCRM$_s$ incorporating 10%, 20%, and 30% natural perlite powder as a cement replacement were evaluated in the fresh and hardened states as well as the durability properties in comparison to a control mortar with 100% cement.

2. Experimental program

2.1 Material properties

In this study, perlite powder (Fig. 1) was used as a mineral admixture, complying with standard specifications for pozzolanic materials ASTM 618 (2012). It is mined from a quarry owned by the

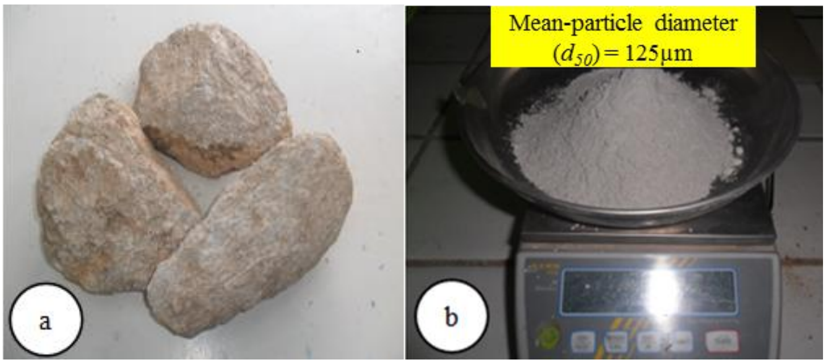


Fig. 1 Photographic view of natural perlite rock (a) and (b) perlite powder

Table 1 Physical and chemical properties of Portland cement and perlite powder

Property		Cement	Perlite
Physical properties	Initial setting time (minutes)	170	--
	Final setting time (minutes)	225	--
	Specific gravity	3.10	2.38
	Blaine specific surface area (m^2/kg)	340	500
	28-day compressive strength (MPa)	42.5	--
Chemical properties, basic oxides (%)	CaO	63.40	1.42
	S_iO_2	21.60	71.73
	Al_2O_3	4.45	13.43
	SO_3	1.92	0.01
	Fe_2O_3	5.35	1.4
	MgO	1.65	0.42
	Na_2O	0.11	3.12
	K_2O	0.22	4.33
	LOI	0.78	3.66

Table 2 Physical properties of sand and coarse aggregates

Properties	Sand	Coarse aggregate
Specific gravity	2.42	2.56
Fineness modulus	1.65	--
Absorption	0.78	--

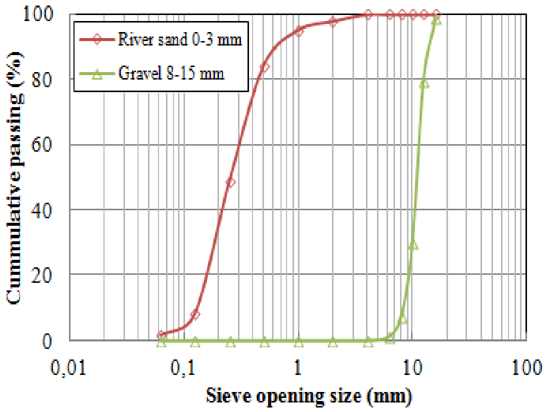


Fig. 2 Particle-size distribution of fine and coarse aggregates

Bental Company (Hammam Boughrara, in North Western Algeria). The perlite material was grinded with a laboratory pulverizer to a particle-size distribution (PSD) with a mean-particle diameter (d_{50}) of 125 μm. Their physical and chemical properties are listed in Table 1.

Ordinary Portland cement used in this study was produced according to EN197-1 (2000) European Standards and referred as CEM I 42.5. The physical and chemical properties of cement were obtained in laboratory and summarized in Table 1.

River siliceous sand with the properties given in Table 2 was used as fine aggregate in the mortar and concrete mixtures. Crushed limestone sourced from a local quarry was used as coarse aggregate. It had nominal maximum size (MSA) of aggregate of 15 mm and specific gravity of 2.56 (Table 2). The PSD of the fine and coarse aggregates determined by sieve analysis are presented in Fig. 2.

The superplasticizer which was used in mortar mixes, is a polycarboxylate ether conforming EN 934-2 (2009) specifications, with a density of 1.065 g/cm^3 and solid content of 30%. PPF fiber of 12 mm in length and 0.3 mm in diameter with a density of 0.9 g/m^3 and modulus of elasticity of 3 kN/mm^2 was used in this investigation.

2.2 Mixture proportions and mixing sequence

Three repair mortar mixtures containing 10%, 20%, and 30% perlite powder as partial cement replacement in addition to one control mortar with 100% cement were prepared according to the requirements of the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC 2005). Table 3 presents the composition and names of the FR-SCRM mixtures. The number at the end of each mixture name refers to the replacement ratio of the perlite powder. For example, the FR-SCRM0 is the control mortar (0% perlite powder and 100% cement),

Table 3 Mixture proportions of repair mortar mixtures and substrate concrete

Repair mortars	Cement (kg/m^3)	Perlite (kg/m^3)	Water (kg/m^3)	Paste volume (L/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	*w/b*	SP (kg/m^3)	PPF (%)
FR-SCRM0	788	0	278	542	--	1170	0.35	10.3	0.03
FR-SCRM10	710	79	278	550	--	1170		10.5	
FR-SCRM20	631	158	278	558	--	1170		11.1	
FR-SCRM30	552	237	278	566	--	1170		11.4	
Substrate concrete (C)	340	--	170	--	1130	720	0.5	--	--

while FR-SCRM20 refers to the mortar with 20% cement replacement with perlite powder. After some preliminary investigations, the water-to-powder ratio (*w*/*b*) was selected as 0.35 and the total powder content was fixed at 788 kg/m^3. In the four mortar mixtures, the volume fraction of the polypropylene fiber (PPF) was kept constant at 0.03%.

The substrate concrete (C) prepared in this study is a common concrete typically used by Algerian construction companies. The mix proportion of the substrate is also presented in Table 3.

2.3 Mixing sequence

The production of all repair mortars followed the mixing sequence to achieve similar homogeneity of all mixtures. A standard mixer with a capacity of 5 liters was used. The sand, cement, and natural perlite powder, if applicable, were added to the mixer bowl. During mixing for 2.0 min, two thirds of the mixing water was added slowly. The superplasticizer diluted in the remaining water was then added, and mixing was continued for additional 3.0 min. During the mixing, the PPF were dispersed manually in the mixture according to the technical instructions provided by the manufacturer. Upon the mixing terminal, the fresh tests were conducted.

2.4 Testing methods

The slump flow diameter using mini-slump cone and flow table, visual indices for bleeding and segregation, and flow time using mini V-funnel test were measured for each of the four mortar mixtures in the fresh state. All these tests were conducted in accordance with the procedures recommended by EFNARC (2005).The unit weight of fresh and hardened mortars was determined according to the European EN 1015-6 (1998) and EN 1015-10 (1999) Norms, respectively.

The compressive and flexural strengths are the most important criteria for classifying repair material according to the EN 1504-3 (2006). For this purpose, prism specimens measuring 40×40×160 mm were prepared for both compressive and flexural strengths for each repair mortar according to EN 12190-6 (1999). The flexural and compressive strength tests were carried out at the ages of 2, 7, 28 and 91 days. For each repair mortar, the compressive strength was determined by taking the average of six test results, whereas the flexural strength was determined as an average of three samples.

For the substrate concrete, the compressive and splitting-tensile strengths were determined using 100×200 mm cylinders, where prisms measuring 70×70×280 mm were prepared for the flexural strength test.

The dynamic modulus of elasticity (E_D) for all repair mortars was determined by the resonant frequent method using the ultrasonic pulse velocity test (UPVT). The test was performed on

Fig. 3 slant-shear specimen under compression testing

cylindrical specimens measuring 100 mm in height and 50 mm in diameter after 2, 7, 28, and 91 days of water curing according to EN 12504-4 (2005). After determining the ultrasonic velocity through the specimen, the E_D is calculated using Eq. (1).

$$E_D=\rho V^2 \tag{1}$$

where:

E_D: Dynamic modulus of elasticity (GPa)

ρ: Density of dry specimen (kg/m^3)

V: Ultrasonic velocity (m/s)

The coefficient of capillary water absorption was measured according to the European standard EN 1015-18 (2002). After 28 days of water curing, the FR-SCRM$_s$ prism specimens(40×40×80 mm) were oven dried at 60℃ for a at least 48 h until mass stabilization. A resin layer was used to cover the lateral sides of the prisms. The dry mass of the prisms were noted, and then they vertically placed over a grid in a water tight tray containing 5-mm water depth. The coefficient of water absorption was evaluated as the water mass absorbed in the prisms during 24 h of exposure.

The adhesion between repair mortars and concrete substrate (C) was characterized with slant-shear test according to ASTM C882 (1999). The slant-shear test can represent typical cases in the real structures (Climaco and Regan 1989) and produces reliable results (Knab 1989). The specimen used in the slant-shear test consisted of two halves of a cylinder bonded at 30°. One half cast with repair mortars (FR-SCRM$_s$) and bonded to a second half cast with the substrate concrete (C). The composite cylinder was tested under axial compression (Fig. 3).

The substrate part of the specimen was cast using plastic molds positioned at 30° inclination angle and cured for 28 days in water. The inclined surface of the samples was treated by wet sandblasting (crushed sand of 1 mm diameter under 7 MPa pressure). The substrate parts were stored for 1 year in ambient laboratory temperature before casting the FR-SCRM$_s$ on top of it. The interfaces of the substrate samples were saturated in water for six hours and surface dried before casting the FR-SCRM$_s$. The repair mortars were cast on the top of the substrate concrete specimen and then cured inside polyethylene bags at a relative humidity (RH) of 95±5% and a temperature of 20±2℃. The composite cylindrical samples were topped with a sulphur layer for surface leveling, and then tested in compression according to ASTM C39 (2003) at ages of 1, 7, and 28 days. The bond strength using the slant-shear test can be calculated using Eq. (2).

$$\tau = \frac{F_{max}}{(\pi \times \varphi^2)} \times 4 \times \sin 30° \tag{2}$$

where:

τ: bond strength (MPa)

F_{max}: maximum applied force (kN)

ϕ: diameter of cylinder (mm)

3. Results and discussion

3.1 Fresh and rheological properties of mortar mixtures

The visual inspection of the four tested mortar mixtures showed no evidence of bleeding or segregation. The other fresh and rheological properties (slump, V-Funnel flow time, and unit weight) for the tested repair mortars are detailed in the following sections.

3.1.1 Mini-slump flow

The results of mini-slump flow diameters are plotted in Fig. 4. A target slump flow diameter of 250±10 mm according to EFNARC (2005) for repair mortars was secured by adjusting the HRWRA dosage. The obtained slump flow diameters were in ranges of 243 to 260 mm. It can be seen from the figure that the required HRWRA dosage to achieve the target slump flow slightly increased with increasing the amount of perlite powder. It was clear in Table 3, in the case of FR-SCRM0, 10.3 kg/m^3 of HRWRA was used, while FR-SCRM10, FR-SCRM20 and FR-SCRM30 included 10.5, 11.1 and 11.4 kg/m^3, respectively. This could be explained by high internal porous structure and high fineness of natural perlite (Blaine fineness of 500 m^2/kg for the perlite powder vs. 340 m^2/kg for cement), which led to higher adsorption of the free mixing water and consequently increased HRWRA dosage to secure the target slump flow.

3.1.2 Mini v-funnel flow time

The flow time obtained from the mini V-Funnel test for the four repair mortar mixtures were found to vary between 9 and 11 s, as presented in Fig. 5. The use of 10%, 20%, and 30% perlite powder was observed to increase the flow time (9.6, 10.2, and 11s for FR-SCRM10, FR-SCRM20 and FR-SCRM30, respectively) compared to a 9 s measured for the FR-SCRM0. It has to be noted that all investigated repair mortars satisfied the allowable flow-time requirements (greater than 7 s) specified by the EFNARC (2005).

The increase in the flow time for the mortars containing perlite powder compared to that with 100% cement (FR-SCRM0) can be explained by the high amount of powders used in these three mixes compared to the powder content used in the FR-SCRM0 (Hunger 2010). In other words, a partial replacement of cement by perlite powder results in higher volume due to the lower density of perlite powder (see Table 1). This results in an increase in the paste volume yielding to higher viscosity of the mixture, and thus leads to reduce fluidity (longer flow time) (Sahmaran *et al*. 2006, ACI 232.1R-00 2000, Yahia *et al*. 2005).

3.1.3 Fresh unit weight

Fresh unit weight values for the four repair mortars varied between 2297 and 2178 kg/m^3, as given in Table 4. The highest unit weight of 2297 kg/m^3 was measured for the mortar designed with 100% CEMI, while the lowest value of 2178 kg/m^3 was obtained for the FR-SCRM30 designed with the highest perlite powder content of 30%.This was attributed to the lower specific unit weight of the perlite powder than that of cement (Table 1) (Hasan *et al.* 2015).

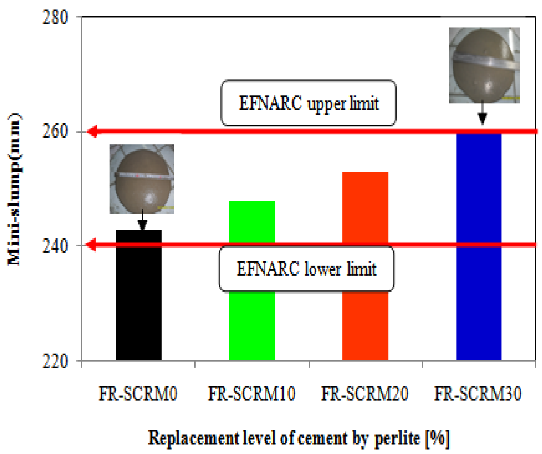


Fig. 4 Mini-slump flow of the FR-SCRM$_s$

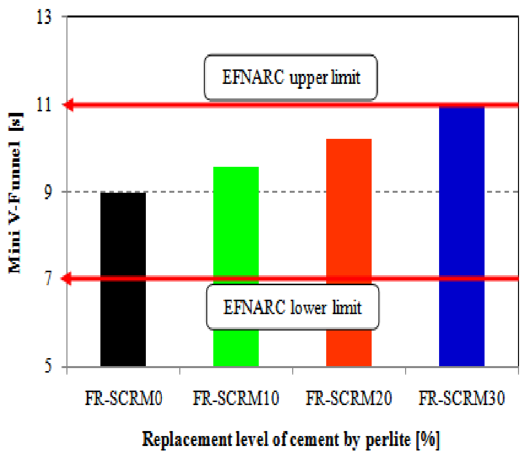


Fig. 5 Mini V-Funnel flow time of the FR-SCRM$_s$

Table 4 Results of unit weight of the specimens during the tests

Mortar codes	FR-SCRM0	FR-SCRM10	FR-SCRM20	FR-SCRM30
Fresh unit weight (kg/m^3)	2297	2244	2214	2178
Air dry unit weight (kg/m^3)	2209	2165	2105	2053

3.2 Hardened properties of mortar mixtures

3.2.1 Air-dry unit weight

The results of 28-day air-dry unit weight for repair mortars made with perlite powder and the control mortar FR-SCRM0 are also shown in Table 4. The hardened unit weight values present the same trend as the fresh unit weight regarding the decrease of the unit weight at higher replacement ratios of cement by perlite powder. Furthermore and as expected, the hardened unit weight values (varied between 2209 and 2053 kg/m^3) were lower than those at the fresh state. Again, in all repair mortars, the lowest dry unit weight was obtained for FR-SCRM30 (2053 kg/m^3), which was lower by 7% than the FR-SCRM0. This is probably due to the inclusion of perlite powder in the FR-SCRM$_s$ mixtures produced porous structure, which led to a reduction in the unit weight of mortar mixtures (Burak 2015). Such reductions in unit weight are desirable in point of decreasing dead load of repaired structures.

3.2.2 Compressive and flexural strength results

The evolution of compressive and flexural strengths with time for the FR-SCRM$_s$ made with perlite powder and control mortar FR-SCRM0 are plotted in Figs. 7 and 8, respectively. At all

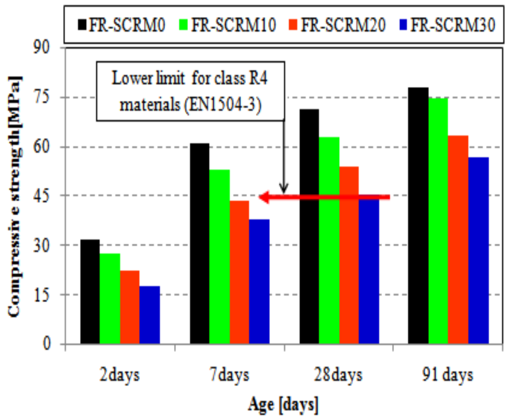


Fig. 7 Compressive strength results of FR-SCRM$_s$, at different ages

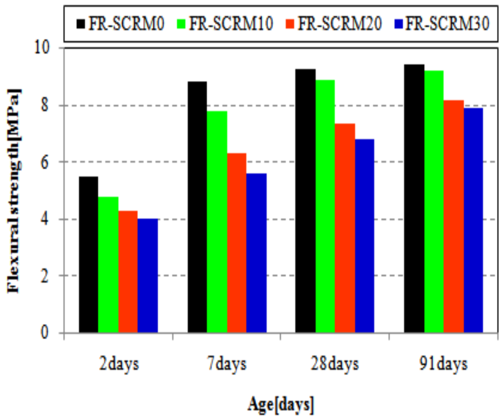


Fig. 8 Flexural strength results of FR-SCRM$_s$, at different ages

ages, the compressive strength values of the mortars containing perlite powder were lower than that of the FR-SCRM0. The higher compressive strength value was reported for the FR-SCRM0, followed by the FR-SCRM10, then FRSCRM20, and at the end FR-SCRM30. This finding is consistent with the observation of Turanli *et al*. (2005). At early age (2 days), the reductions in the compressive strength values for the FR-SCRM10, FR-SCRM20, and FR-SCRM30 compared to the FR-SCRM0 were about 14%, 30%, and 44%, respectively. The corresponding ratios at 7 days were 13%, 29%, and 38%, respectively. Those ratios at 28 days were 12%, 24%, and 36%, while at 91 days were 5%, 19%, and 27%, respectively. Based on the results, the compressive strength of the mortars containing perlite powder is closely related to their density. Indeed, higher replacement level of cement by perlite powder results in more porous microstructure, leading to lower density of the mortar and consequently lower compressive strength. In addition, the pore space affects both the nucleation as well as the development of hydrates. In this study, perlite had low reactivity at 7-day age (reducing compressive strength). At later ages (91 days), the compressive strengths of mortars with perlite powder were improved due to development of the pozzolanic reaction. The mortars containing perlite powder exhibited significantly higher compressive strength gain than that of the FR-SCRM0. This can be illustrated from the values of the reductions in the compressive strength with time. For example, the compressive strength reductions for the FR-SCRM10 mixture were 14%, 13%, 12%, and 5% at the ages of 2, 7, 28, 91 days, respectively. It can be noticed that the 91-day compressive strength for 10% substitution level approached that of the control mortar (only 5% reduction). This accelerated rate of strength development with time was due to the pozzolanic reactivity of the perlite powder. This can be explained by the greater amount of secondary hydrates (C-S-H) formed during pozzolanic reactions with the lime resulting from the primary hydration products of cement which fill the voids in the mortar with perlite powder compared to the control. This finding is consistent with the results reported by Uzal *et al.* (2007).

It is important to note that all the investigated repair mortars had 28-day compressive strength values higher than 45 MPa, fulfilling the requirements of class *R*4 materials according to the EN 1504-3 Standards.

A similar tendency was observed for the flexural strength development with time, as shown in Fig. 8. At early age (7 days), the reductions in flexural strength values of FR-SCRM10, FR-

SCRM20, and FR-SCRM30 compared to the FR-SCRM0 were, 11%, 29%, and 36%, respectively, while at later age (91 days), these reductions were significantly changed to only 3%, 14%, and 17%, respectively. The reduction in the flexural strength measured for the 10% perlite substitution (FR-SCRM10) at 91 days was very close to that of the control due to the positive effects of pozzolanic reaction.

3.2.3 Dynamic modulus of elasticity

The values of the dynamic modulus of elasticity (E_D) for the repair mortars obtained using cylindrical specimens at 2, 7, 28, and 91 days are shown in Fig. 9. The results demonstrate that the E_D follows the same trend of the compressive strength, where the perlite powder affected also negatively the E_D. Such occurrence could be attributed to the lower elastic modulus of the perlite powder than that of the cement and lower compressive strength of the mortars with perlite powder than that of the control mortar (Chi *et al.* 2003).

The relationship between the E_D and the compressive strength results at 28-days for the repair mortars are very strong with a coefficient of correlation (R^2) of 0.99, as illustrated in Fig. 10. At early age (2 days), the E_D value of the control mortar was 38.5 GPa compared to 30.4 GPa for the FR-SCRM30 mixture (about 21% lower). At later age (91 days), this ratio was minimized to 16% due to the positive effects of pozzolanic reaction. We found that the E_D value for 10% substitution level in the FR-SCRM10 was 47.1 GPa approaching to that of the control mortar (48.6 GPa).

It is worth noting that at 28 days, all mortars exhibited E_D values higher than the lower limit (20 GPa) required by the EN 1504-3 Standard for class *R*4 repair mortars.

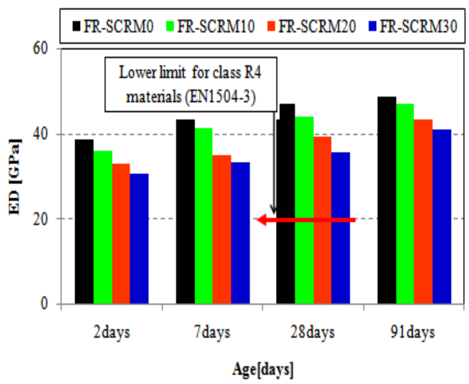


Fig. 9 Results of dynamic modulus of elasticity (E_D) of the FR-SCRMs, at different ages

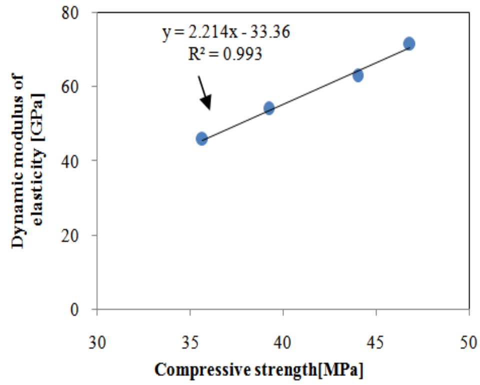


Fig. 10 Relationship between compressive strength and E_D at 28 days

3.3 Durability properties (capillarity water absorption)

The capillary water absorption test results after 24 hours of saturation for the investigated FR-SCRM$_s$ are shown in Fig. 11. The control mortar (FR-SCRM0) of the highest unit weight monitored the lowest water absorption (about 0.23 kg/m^2.h$^{0.5}$). While, the cement replacement by 10% (FR-SCRM10), 20% (FR-SCRM20), and 30% (FR-SCRM30) of perlite powder caused decreases in the density and led to higher water absorption (0.27, 0.36, and 0.42 kg/m^2.h$^{0.5}$, respectively). This finding is consistent with that reported by Lanzon and Garcia (2008) and

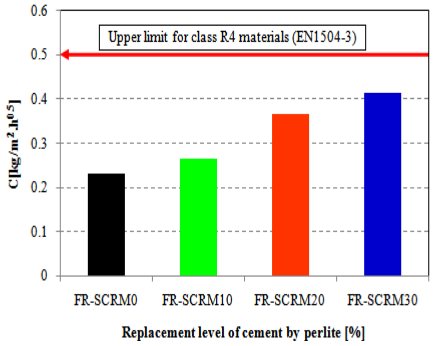


Fig. 11 Water absorption of the FR-SCRM$_s$, after 24 hours

Table 5 Results of slant-shear bond strength

Composite	Max. Force (kN)			Comp. Stress C (MPa)			Shear. Stress S (MPa)		
	1 day	7 days	28 days	1 day	7 days	28 days	1 day	7 days	28 days
FR-SCRM0/C	44.2	108.9	148.4	10.0	24.7	33.6	5.0	12.3	16.8
FR-SCRM10/C	38.0	96.5	143.4	8.6	21.9	30.9	4.3	10.9	16.2
FR-SCRM20/C	31.7	88.0	130.2	7.2	19.9	29.5	3.6	10.0	14.7
FR-SCRM30/C	25.6	70.5	123.1	5.8	16.0	27.9	2.9	8.0	13.9

Khonsari *et al.* (2010).

Indeed, the water absorption values for all investigated repair mortars that range between 0.23 and 0.42 $kg/m^2.h^{0.5}$ satisfy the requirements (less than 0.5 $kg/m^2.h^{0.5}$) for the building materials to be used in structural applications class *R*4.

3.4 Bond strength (slant-shear test)

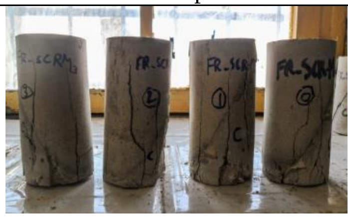
The substrate concrete (C) was test at 28 days after casting and the results of the compressive, flexural, and splitting-tensile strength values were 30, 5.75, and 2.35MPa, respectively.

The slant shear strengths of the FR-SCRM10, FR-SCRM20, and FR-SCRM30 mortars with respect to that of the control mortar FR-SCRM0, after different curing ages were obtained from the compressive strengths of composite cylindrical specimens with the substrate concrete (C). The slant shear strengths and the failure modes of composite cylindrical specimens' results at 1, 7, and 28 days are presented in Tables 5 and 6, respectively.

Three different failure modes were observed for the tested composites in the slant shear test. At 1day, the failure type for all repair mortars was interface separation. At 7 days, a monolithic failure mode appeared with the propagation of crack through the repair mortars and concrete substrate (C) for all specimens. We found that the substrates were greatly damaged, however some cracks in the repair mortars were observed. At 28 days, all the composites had failure through the substrate concrete (C), except for the FR-SRCM30/C composite that presented a monolithic failure similar to the one at 7 days.

The data show that the slant shear strength decreases with the reduction of cement content (increase of the perlite powder) in mortars containing perlite. This can probably attributed to the weaker perlite powder, which creates large voids spaces and porous structure. For instance, at 1, 7,

Table 6 Mode of failure for composite specimens in slant-shear test

Age (day)	Failure mode	ACI Bond strength range
1	 Interface separation	2.8 to 6.9
7	 Monolithic failure	6.9 to 12.4
28	 Monolithic failure Substrate failure	13.8 to 20.1

and 28 days, the FR-SCRM10/C showed 14%, 11%, and 4%, lower bond strength than those of FR-SCRM0/C control. Whereas in the case of FR-SCRM30/C, the corresponding ratios were significantly higher (42%, 35%, and 17%, respectively). One of the possible reasons of the strong bonding between FR-SCRM10 and the substrate (C) is the use of higher amount of cement in the FR-SCRM10 mixes compared to the FR-SCRM20 and FR-SCRM30 mixes. The higher cement content can penetrate into the pores on the surface of perlite powder and consequently increase the interfacial zone (Bogas *et al.* 2014). It is interesting to note that all the repair mortars exhibited greater slant shear strength values than the lower limit of slant shear strength values (Table 6) specified by the Concrete Repair Guide-ACI 546R (2004).

5. Conclusions

This study demonstrates that it is possible to use local mineral fillers, like natural perlite powder, to produce fiber-reinforced self-consolidating repair mortars (FR-SCRM$_s$). The perlite powder can partially replace cement by up to 30% while maintaining the Standard specifications for the repair mortar in terms of flowability, strength, durability, and adhesion. From this investigation, the following conclusions can be drawn:

• Using perlite powder in FR-SCRM$_s$ requires slight increase of the superplasticizer dosage to secure the same workability.

• The perlite powder of the higher fineness than cement leads to increasing the viscosity of the mortar mixtures. This can represented by the relatively longer flow time of the V-Funnel test.

• The use of perlite powder can provide light repair mortar due to the voids and porous structure created by the perlite as well as its lower density.

• The partial replacement of cement by perlite powder reduces the mechanical strength (compressive and flexural) of mortars and this reduction is higher at the higher replacement levels. The rate of strength development over time is more pronounced for the mortar mixtures containing perlite powder due its pozzolanic reactivity. All the investigated repair mortars fulfill the requirement (28-day compressive strength of 45 MPa) for Class *R*4 repair material according to the EN 1504-3 Standards.

• Dynamic modulus of elasticity of mortar decreases with the reduction in the cement content (increase of the perlite substitution level).This reduction improves at later ages (91 days) due to the pozzolanic reaction of the perlite powder. The investigated repair mortars confronted the minimum requirements for class *R*4 repair materials according to the EN 1504-Standards (20 GPa at 28 days).

• The water absorption values (0.23 $kg/m^2.h^{0.5}$ to 0.41 $kg/m^2.h^{0.5}$) for all repair mortars, after 24 hours of water submersion satisfy the requirements (less than 0.5 $kg/m^2.h^{0.5}$) for the class *R*4 building materials to be used in structural applications. The water absorption for the FR-SCRM with perlite powder is higher than that of the control due to the lower density and porous structure of the former mortars.

• The slant shear strength depends mainly on the compressive strength of repair mortars. Three different failure modes were observed in this slant shear test: interface separation at 1 day, monolithic at 7 days, and substrate failure at 28 days. All the investigated repair mortar composites exhibited greater slant shear strength values than lower limit of slant shear strength values specified by the ACI at 1, 7, and 28 days.

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