Computers and Concrete, *Vol. 20, No. 3 (2017) 283-290*
DOI: https://doi.org/10.12989/cac.2017.20.3.283

Influence of ground pumice powder on the bond behavior of reinforcement and mechanical properties of self-compacting mortars

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(Received February 22, 2017, Revised March 27, 2017, Accepted April 24, 2017)

Abstract. The aim of this study is to investigate the effect of the bond strength of self-compacting mortars (SCMS) produced from ground pumice powder (GPP) as a mineral additive. In this scope, six series of mortars including control mix were prepared that consist of 7%, 12%, 17%, 22% and 27% of ground pumice powder by weight of cement. A total of 54 specimens of 40×40×160 mm were produced and cured at the age of 3, 28 and 90-day for compressive and tensile strength tests and 18 specimens of 150×150×150 mm mortar were prepared and cured at 28 days for bond strength tests. Flexural tensile strength and compressive strength of 40×40×160 mm specimens were measured at the curing age of 7, 28 and 90-day. Mini V-funnel flow time and mini slump flow diameter tests were also conducted to obtain rheological properties. As a result of the study, it was observed that the SCMs containing 12% of GPP has the highest bond strength as compared to control and GPP mortars. Compressive strength slightly increased up to 12% of GPP.

Keywords: self-compacting mortar; ground pumice powder; bond strength; fresh properties; mechanical properties

1. Introduction

Mineral admixtures replace cement in mortar mixtures and in some concrete types such as self-compacting, reactive powder, compacted cylinders and lightweight concrete. Mineral additives are used to improve the mechanical properties of the mixture due to pozzolanic and/or self-cementing. Pumice is a lightweight material with a volcanic origin produced by the release of gases during the solidification of lavas. The cellular structure of the pumice is formed by the presence of molten lava flowing through volcanoes when cooled (Kabay *et al*. 2015, Hossain 2004). Light aggregated pozzolanic materials may have some cementitious properties when made into very fine powder. At the same time, when they are mixed with a certain amount of cement and lime, their binding property increases (Kabay *et al*. 2015, Sahin *et al*. 2008). The pumice is in fact an aluminum silicate shaped by a cellular structure of explosive volcanism and is widely used as building material due to its cellular structure, lightweight and insulation properties (Aydin and Baradan 2007). In 2014, pumice and pumicite production used or sold increased to 285.000 metric tons which was 269.000 metric tons in 2013. Turkey and Italy are the leading producers of pumice and pumicite. The pumice was used in building block production of approximately 56%; Gardening consumption is 18%; Concrete admixture and aggregate, 12%; Abrasives, 10%; the remaining 4% was used for absorbent, filtration and other applications (Hossain 2008, Beycioglu *et al*. 2015). Self-compacting concrete (SCC) has recently emerged as a new concrete technology and its use has increased rapidly over the last three decades and reflected in the number of published works. Self-compacting mortar (SCM) exhibits similar mechanical and durability properties to SCC and can be used to examine the performance mechanisms of the SCC (Sahmaran *et al*. 2006). Mortar forms the basis of the workability properties of self-compacting concrete (SCC) and these properties can be evaluated with self-compacting mortars (SCM). In fact, evaluating the properties of the SCM is an integral part of the SCC design (Sahmaran *et al*. 2006, Domone and Jin 1999). Self- Compacting Concrete (SCC), which offers benefits in workability, reduces labor costs and high strength compared to conventional concrete, is one of the latest developments in concrete technology (Sahmaran *et al*. 2006, Uysal and Yilmaz 2011). Super plasticizing chemical additives, powder material and/or viscosity regulators which reduce water at high levels in SCC production are used (Sonebi 2004, Mohamed 2011, Da Silva and De Brito 2015). While the use of superplasticizer maintains fluidity, it ensures the stability of the fine-content mixture and thus obtains resistance against bleeding and separation. Due to the low density of aggregate used in concrete, strength and workability loses increase and segregation occurs in concrete. High strength, durability and segregation resistance properties of SCC can fix mentioned problems of lightweight concretes. Unlike conventional concrete, using of chemical additives, superplasticizer and pozzolanic

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http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

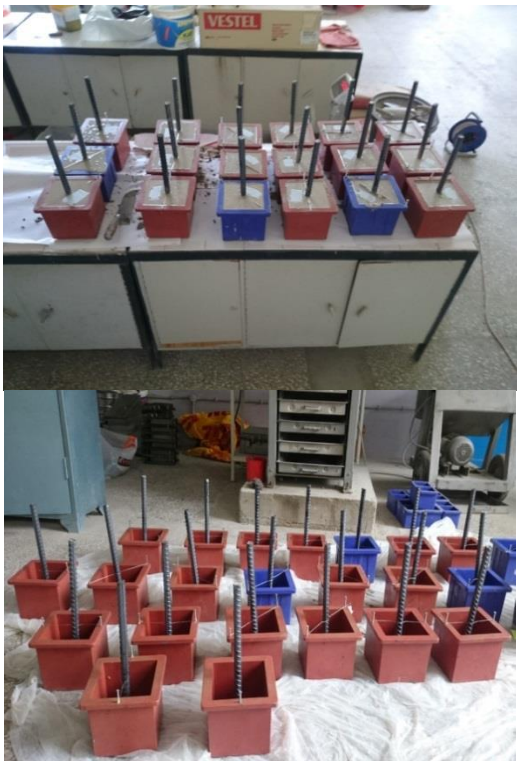


Fig. 1 150×150×150 mm cube specimens for pull out tests

mineral additive are needed in SCC. New standards and test methods are being developed for the selection and use of these materials in concrete design (Karatas 2010, Shetty *et al*. 2014). Standards issued by EFNARC were used in this study. According to EFNARC; workability of self-compacting concrete can be provided with filling capability, suitable viscosity determined by the flow rate, the ability to pass through the narrow section and the separation resistance (Karatas 2010). Limiting amount of coarse aggregate is common method to achieve the high fluidity of SCC. Besides, it is necessary to increase the proportion of fine material. For this purpose mineral additives such as ground pumice, fly ash, limestone powder, slag and silica fume can be used in concrete (Bonavetti *et al*. 2003, Bosiljkov 2003). Furthermore, the benefits of using mineral additives in concrete are protecting nature and providing economy. One of the most important properties of reinforced concrete construction is bond strength (Campione and La Mendola 2004, Turk and Yildirim 2003). The bond between the concrete and the steel rebar allows redistribution of loads and moment. This event causes reinforced concrete existence. Many experimental methods have been used to determine the bond mechanisms between concrete and steel rebar (Deng *et al*. 2014, Golafshani *et al*. 2014). The simplest and often used bond test is a pull-out method. (Beycioglu *et al*. 2015) limited published studies dealing with the bond characteristics of concrete or mortar produced from pumice. Hossain (2008) explored the bond properties of plain and deformed reinforcing bars in lightweight volcanic pumice concrete (VPC) and normal concrete (NC). According to the author, the most important result was that the bond strength of bars deformed in lightweight VPC was lower than in NC. Beycioglu *et al*. (2015) studied to determine the bond performance of lightweight concretes produced using pumice aggregate coated with colemanite-cement paste using hinged beam approach. He concluded that colemanite-cement coated pumice aggregate increases compressive strength and bond performance of the lightweight concretes. Sancak *et al*. (2011) investigated the bond strength between concrete and steel reinforcement of structural concrete produced by lightweight pumice aggregate (SLWAC) and the normal-weight aggregate (NWAC) without additives**.** The result showed that the bond strength of deformed bars in SLWAC was lower compared to those of NWAC. Naik *et al*. (1989) presented some pull-out tests on samples using fly ash (FA) to replace 10-30% of Portland cement and evaluated the effect of the curing temperature on bond strength. The results show that bond strength at normal temperatures can be improved until about 20% FA replacement at which level bond strength began to decrease. Dybel and Furtak (2014) determined the effect of the silica fume content in concrete on the reinforcing steel-High performance concrete bond stiffness. They concluded that the highest bond stiffness was obtained at 5% silica fume content in the concrete, replacing Portland cement.The main objective of this paper is to examine bond performance and the mechanical properties of SCMs containing ground pumice powder. In this study, six mixtures were used, which were substituted ground pumice powder with cement, and a mixture was used as a control. The fresh characteristics of the SCMs were determined by mini-slump flow diameter and mini and V-funnel flow time. Hardened properties were evaluated by 3, 28, and 90 days of compressive strength and flexural tensile strength tests.

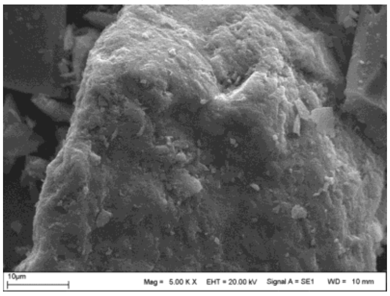
2. Experimental program

In this study, the effect of ground pumice powder on the bond strength of reinforcement was investigated in SCMs. For his purpose, 6 mixtures including control sample were prepared. Three samples were produced from each of these mixtures for each experiment. Self-compacting mortar (SCM) incorporating GPP at the rates of 7%, 12%, 17%, 22%, 27% of the binder by weight were considered. In order to determine the mixing ratios of SCMs according to these pumice rates, mini slump flow test and the V-funnel flow test were conducted. As the GPP ratio increases, the workability is deteriorated, the spreading is prevented, and the stickiness is increased. For this reason, GPP ratio is limited to 27%. Three series of specimens with the dimensions of 40×40×160 mm were cast with various GPP contents for compressive and flexural testing of SCMs. after demolding the specimens; they were cured at the age of 3, 28 and 90-day at 20±2℃. After curing, they were tested to measure the compressive and flexural tensile strength. To investigate the bond strength of reinforcement in SCMs, 150×150×150 mm cube samples (Fig. 1) were prepared and a 20 mm steel bar was placed in the middle of specimen and pull-out test was carried out at the end of 28 days, RILEM 7-11-128 was used as a guide for pull out specimens (three for each concrete mix). The RILEM report recommends the use of concrete cubes with a rod in the middle and a clear cover 4.5 times the diameter of the rod

Table 1 Properties of Portland cement and ground pumice powder

Chemical Components (%)	PC	GPP
SiO_2	21.12	63.57
Al_2O_3	5.62	14.81
Fe_2O_3	3.24	6.75
CaO	62.94	2.66
MgO	2.91	1.02
SO_3	2.48	0.02
Na_2O	-	4.36
K_2O	-	4.36
CI	-	-
Loss in ignition	3,52	4.59
Physical Properties		
Specific Gravity (g/cm^3)	3.03	2.47
Specific Surface Area (cm^2/g)	3430	2871

(a)



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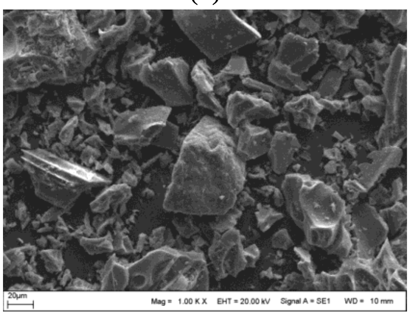


(c)

Fig. 2(a) Ground pumice powder (GPP) (b) 10 μm Mag SEM micrographs of GPP (c) 20 μm Mag SEM micrographs of GPP

on either side of the horizontal cross section. The pull-out specimens of this work were 150 mm diameter cubes to ensure that all the samples failed in the pull-out process.

Table 2 Product properties of superplasticizer

Material structure	Modified polycarboxylates based polymer
Density (gr/cm^3)	1.06
pH	3–7
Freezing point (˚C)	-4
Clor content % (TS EN 934-2)	<0.1
Alcali content % (TS EN 934-2)	<3

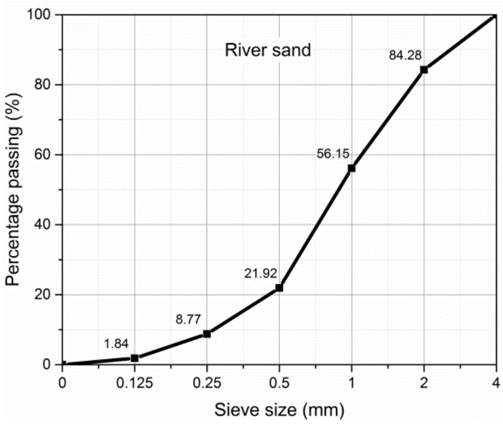


Fig. 3 Particle size distribution of natural river sand

2.1 Materials

An ordinary Portland cement (CEM I 42.5N) was used to produce SCM mixtures. The pumice used for the study was obtained from the Ahlat region of Bitlis. The amount of grinding pumice passing through the 0.125 mm sized sieve was determined to be 85% used as mineral admixture. The chemical components and physical properties of cement and GPP are presented in Table 1. Fig. 2 illustrates the ground pumice powder (GPP) and the SEM micrographs of GPP.

The fine aggregates used in the mixtures were natural river sands with specific gravity, fineness modulus and water absorption of 2.63 gr/cm^3, 3.27 and 1.94% respectively. The maximum grain size of sand was 4.00 mm (Fig. 3).

In addition, a modified polycarboxylate-based polymer type superplasticizer (SP) is required to achieve a suitable consistency with a low water/binder (W/B) ratio. The specific gravity of SP used was about 1.06 g/cm^3 and pH in the range of 3-7. The used SP was kept constant in all the blends and was set at 7 kg/m^3.

2.2 Mix proportions and fresh mortar tests

A total of 6 different mixtures containing 650 kg/m^3 binder, including the control sample, were prepared to observe bond strength of reinforcement and the behaviour of the SCM in fresh and hardened states. Mini slump flow diameter and mini V-funnel flow time tests were performed to determine the rheological properties of SCMs containing GPP. SCM is produced with binary mixes of GPP instead of cement by weight, by the ratios of 7%, 12%, 17%, 22% and 27%. The mixing ratios of the produced blends (for 1 m^3 by weight) are given in Table 3. The SCMs are designed to

Table 3 Mix proportion of mortars (kg/m^3)

Mix Code	Amount of Ingredient (kg/m^3)					
	Binder		Sand	SP*	w/b(by volume)	w/b(by mass)
	PC	GPP				
Control	650	0	1388	7	1.18	0.38
GPP7	604.5	45.5	1375	7	1.16	0.38
GPP12	572	78	1358	7	1.16	0.39
GPP17	539.5	110.5	1340	7	1.17	0.39
GPP22	507	143	1315	7	1.19	0.40
GPP27	474.5	175.5	1305	7	1.17	0.41

*SP=superplasticizer

give a slump flow diameter of 240-260 mm obtained by modifying the SP quantities. The water/binder ratios of the mortars were also determined to be between 0.38 and 0.41. Experimental batches were produced for each mix to obtain the desired sump flow diameter. Slump flow diameter and V-funnel flow time were measured according to the procedure recommended by the EFNARC committee. GPP denotes mortars containing ground pumice powder. The number after each letter GPP indicates the amount of mineral admixture in the mortar. For example, the GPP 12 mortar consists of 12% ground pumice powder.

2.3 Preparation and casting of test specimens

For this work, in all the mixes, cement, mineral additive and sand were first mixed for 1 min. Then, SP and water were poured and mixed for an additional 4 min. A total of 54 specimens of 40×40×160 mm in dimensions, 9 specimens of each mixture for flexural and compressive strength tests, and 18 specimens of 50×50×50 mm, 3 specimens of each mixture were poured to determine bond strength of reinforcement. The workability of fresh mortar was obtained using mini slump and V-funnel test as per EFNARC. During the tests carried out to define mini slump flow diameter and mini V-funnel flow time, segregation and bleeding were visually observed. The compressive and flexural tensile strengths were conducted on 160×40×40 mm prisms after 3, 28 and 90 days in water curing. For bond behaviour of steel test, 150 mm cube samples, cured in water for 28 days, were used.

2.4 Test methods

2.4.1 Workability tests for fresh concrete

The mini slump flow test and the V-funnel flow test were performed according to EFNARC (2002) while measuring workability of SCM. In the mini slump flow test, the truncated cone was filled with mortar on a flat plate and lifted upwards. The diameter was evaluated by averaging the two perpendicular diameters of the mortar. In the V-funnel flow test, after fully filling the funnel with mortar, the bottom outlet was opened to allow the mortar to flow out. The V-funnel flow time was the time (t) between the opening of the bottom outlet and the start of the funnel from the beginning of the light. The workability values of SCMs were considered according to EFNARC (2002) acceptance criteria with 24-26 cm and 7-11 s for slump-flow diameter and V-funnel flow time, respectively.

Fig. 4 Pull-out tests of SCMs

2.4.2 Compressive and flexural strength tests

After the first fresh mortar test is completed, the blends are cast into a 40×40×160 mm steel moulds without any vibration or compaction. Samples were demoulded 24 hours after casting. After demoulding, specimens were cured in in water curing at a temperature of (20±2)℃ until age of testing. The SCMs samples were cured at the age of 3, 28 and 90- day and subjected to flexural tests and compressive tests were conducted following the flexural tests on the two broken pieces as prescribed in ASTM C348 (2002) and ASTM C349 (2002). The compressive strength and flexural strength measurements were carried out using an UTEST UTCM 6420 testing machine press with a capacity of 250 kN in compression and 150 kN in bending.

2.4.3 Pull-out tests

Pull-out tests were performed to determine the bond strength of reinforcement on cube samples of 150×150×150 mm (Fig. 4). Eq. (1) (Karakoç 1985) is used to find the bond strength.

$$\tau = \frac{P}{\pi \cdot d \cdot l} \tag{1}$$

Here, is the bond strength of mortar in MPa, l is the length of rod embedded in mortar in mm, d is diameter of steel rod embedded in mortar cube in mm and P is the pull-out force in N.

3. Results and discussion

3.1 Fresh-state properties

Relative slump and relative funnel speed values are presented in Figs. 5 and 6. It is obvious that SCM mixtures ensured EFNARC (2002) recommendation for relative slump and relative funnel speed. When Figs. 5 and 6 are examined, it can be seen that the workability is fluctuating depending on the increase of GPP. The use of GPP has not followed a linear path in workability, although it affects the

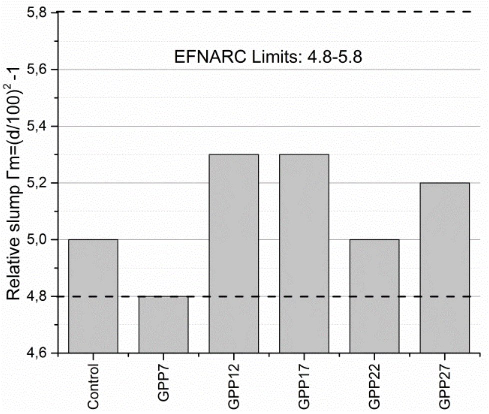


Fig. 5 Relative slump of SCMs

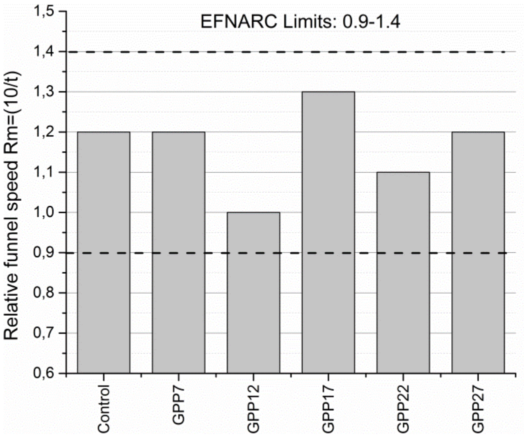


Fig. 6 Relative funnel speed of SCMs

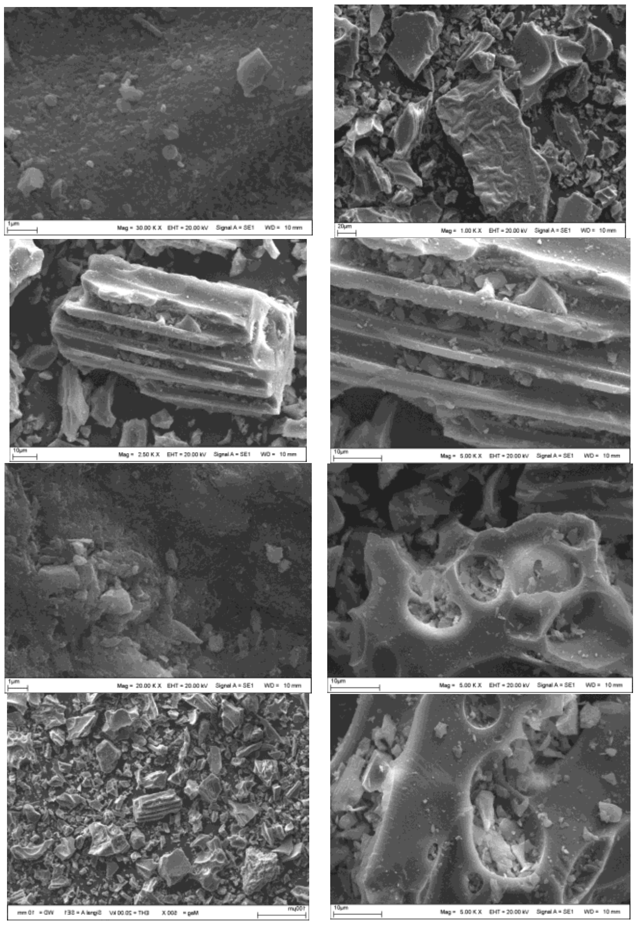


Fig. 7 Microscope images of ground pumice powder

viscosity in the mortar positively. However, in no mortar mixture, it was observed that the EFNARC limit values were not exceeded. Fig. 6 shows the relative funnel speed values that are between 0.9-1.4 as suggested by EFNARC (2002) (Turk 2012, Felekoglu *et al*. 2006).

Fig. 7 presents SEM images of the pumice powder in the mixture. The images show the scaly particles and rounded particles of pumice powder in powder form (at 100 mm scale). The main characteristic of the pumice powder seen is the relative specific pore number and relative specific surface in the SEM, which is an important feature when combined with Pumice powder and cement while the mixture is hydrated. They also give an idea of the size of the micro-pores (at the scale of 10 m scale) and a whole fine round particle. The surrounding scaly particles show the properties of the inner surface of the pores and the distribution of the ultra-fine granulometry (Granata 2015).

3.2 Hardened properties

The compressive and flexural tensile strength development of SCMs with incorporating GPP was plotted in Figs. 8 and 9.

3.2.1 Compressive strength

The average of the compressive strength of the mortars is presented in Fig. 8; where it can be seen that the strength of SCMs with GPP has a lower value in 3 days compared to the reference. This can be explained by the replacement of the cement with a relatively slow reaction GPP (Kabay *et al*. 2015). Hossain reported that the volcanic pumice powder and cement mortars with different contents of cement (up to 25% by weight) caused the compressive strength to decrease at 1, 3, 7 and 28 days. The writer also noted that the reduction in compressive strength was reduced with age. Hossain (2004) concluded that compressive strength of cement mortars with volcanic pumice powder showed a decrease at the age of 1, 3, 7 and 28 days when cement replaced by various contents (up to 25% by weight) The author also remarked that while the age increased, compressive strength continued to reduce. Kabay *et al.* (2015) investigated that as the content of pumice powder increased, compressive strength exhibited a gradual increase by curing time for each mixture and the strength values were comparable to the control at later ages. Granata (2015) studied that mixtures with pumice achieve higher compressive strength after 28 days of curing. He pointed out that that pozzolanicity improves the mechanical properties of the mixture. Binici *et al*. (Binici *et al*. 2014) showed that the compressive and flexural strengths of the mortars at later ages have increased significantly by using blast furnace slag as an additive. However, the compressive strength was lower than those of the reference samples for all the samples with different additive percentages of pumice and barite for all ages. Wen *et al.* (2014) determined that adding pumice as the additive agent in cement composite soil improved the mechanical

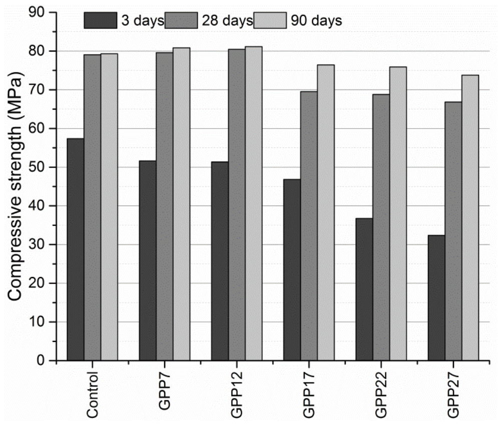


Fig. 8 Compressive strength of SCMs at the age of 3, 28 and 90-day

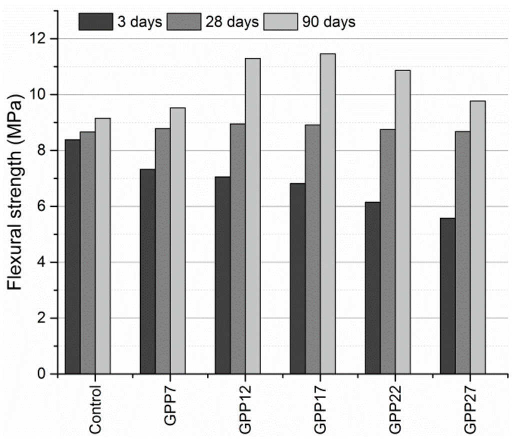


Fig. 9 Flexural tensile strength of SCMs of at the age of 3, 28 and 90-day

properties of soil and early strength of cement composite soil. In this study, the compressive strength values were in the range of 32.4-81.15 MPa, the lowest value belongs to GPP27 at 3 days and the highest value to GPP12 for 90 days.

Compressive strength was lower as compared to control at early ages but at later ages, compressive strength increased gradually when the content of GPP at 12%. As the ratio of GPP increased, a gradual decrease happened in compressive strength at all ages.

3.2.2 Flexural strength

The flexural tensile strength values were in the range of 5.57-11.45 MPa at the age of 3, 28 and 90-day. The lowest value belongs to GPP27 at 3 days and the highest value to GPP17 at 90 days. Fig. 9 shows the flexural tensile strengths of SCMs containing GPP relative to that of the control mixture at 3, 28 and 90 days. As shown in Fig. 9, The pozzolanic activity appears to be more evident when the samples of the pumice, which cannot adequately show its effect on 3 and 28 day samples, have been cured for 90 days (Granata 2015). As the amount of GPP content increased, the tensile strength the mortar increased. After 17 percent of GPP, the increase in GPP content, tensile strength tends to decreases for all curing ages. As the rate of GPP increased, the strength values of the samples cured for

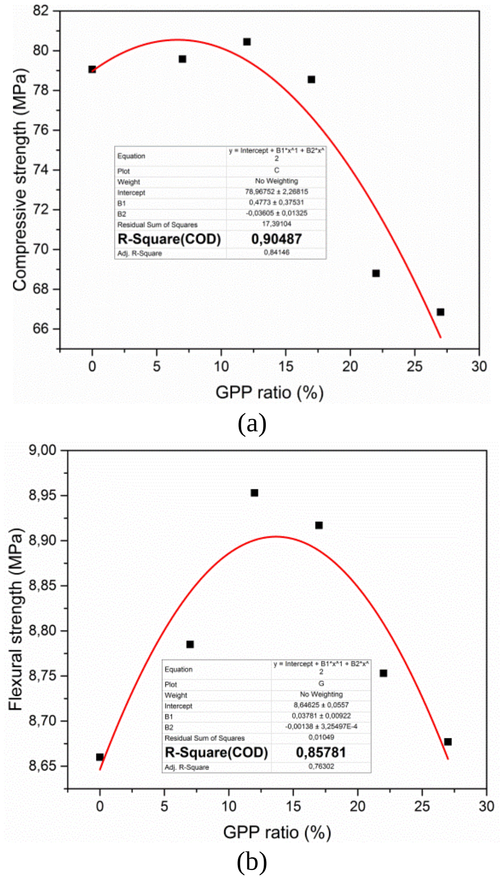
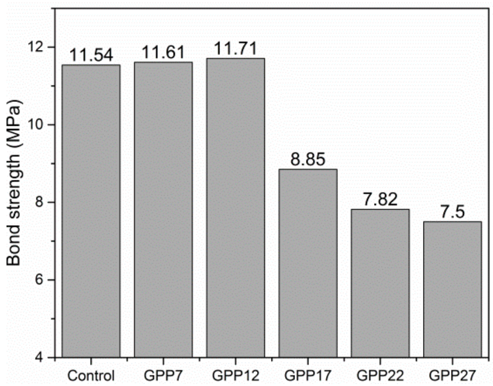


Fig. 10 Variation of (a) compressive and (b) flexural strengths with respect to GPP replacement at the age of 28 d

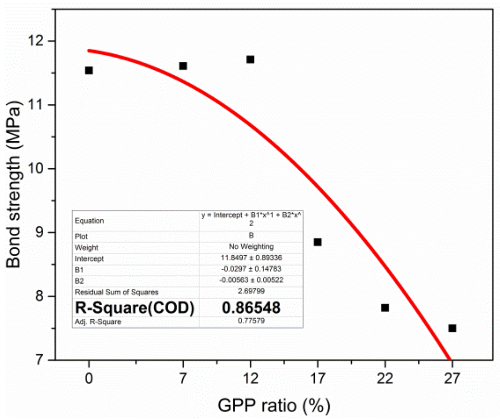
3 days decreased while the strengths of the cured samples remained close to each other for 28 days. As compared to the control sample, while the curing period increases, flexural tensile strength gets higher as compared to control samples. Variation of flexural tensile strength with respect to GPP replacement at the age of 28 days is plotted in Fig. 10(b). As shown in Fig. 10(a), there is a good correlation between the compressive strength and GPP replacement ratio. An optimum GPP replacement content exists between 10-15% replacement ratios of GPP.

3.2.3 Bond strength of reinforcement

Based on the results obtained from the pull out tests, it was determined that the bond strength GPP samples changed according to the rate of GPP. As the GPP ratio increased, a slight increase in the bond strength was observed, followed by a significant decrease as compared to control sample. When the values of bond strength presented in Fig. 11 are examined, it can be determined that bond strength behaves as a concave curve as seen in compressive strength at the age of 28 days. As seen in Fig. 11(a) that the best bond strength obtained in the specimens of 12% GPP, SCMs specimens containing more than 12% GPP, bond strength decreased sharply and remained below the control sample. This reduction may be attributed to the reduction of the used cement by substituting GPP. Because, the strength of mortar will also decrease as the amount of cement decreases. The bond between concrete and reinforcement

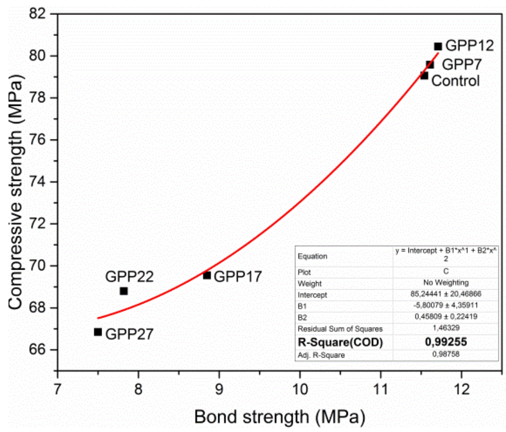


(a)

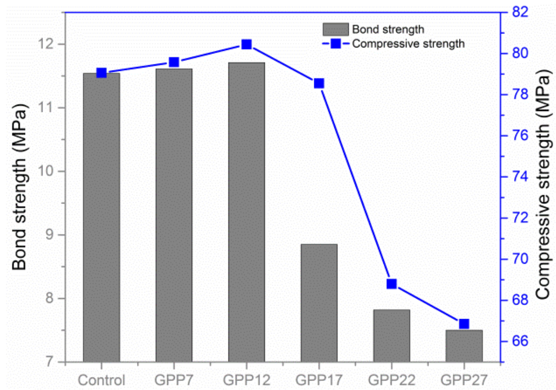


(b)

Fig. 11 (a)Bond strength of SCMs of at the age of 28 (b) Variation of bond strengths with respect to GPP replacement at the age of 28 d



(a)



(b)

Fig. 12 Variation of bond strengths with respect to compressive strength at the age of 28 d

will be weakened due to the decrease in cement ratio. The only problem here is that not only the amount of cement is reduced but also the pumice used as an additive has not yet shown the pozzolanic activity in the desired form during the 28 days of curing. Because, the pumice will begin to contribute more pozzolanic activity with time. In Fig. 11(b), it can be seen that there is a good correlation between the bond strength and compressive strength.

Variation of bond strengths with respect to compressive strength at the age of 28 days is plotted in Fig. 12. As shown in Fig. 12 that there is a strong relationship between bond strength and compressive strength. The strength improvement due to GPP incorporation in mortar occurs due to chemical and physical processes, the chemical effect due to the pozzolanic activity and the physical effect due to the micro filler action. However, decrease in strength is due to the reason that GPP added in excess of that required for pozzolanic and filler actions results in replacement of primary binder, that is cement, and hence reduction in strength.

4. Conclusions

An experimental study was carried out to study the effect of pumice powder on the bond strength of self-compacting mortars and also investigated compressive and tensile behaviour of hardened concrete at different times of curing. Based on the obtained results from this study, the following conclusions can be drawn:

• All of the SCMs mixes examined provide satisfactory fresh self-compacting properties, relative slump and relative funnel speed values remains in the range of EFNARC standard.

• Compressive strength increases gradually as the content of GPP increases to some extent then tends to decreases as compared to control sample.

• At early age, compressive strength is higher than the mixtures containing GPP but at later ages, compressive strength higher than that of control sample.

• The flexural tensile strength increases as in compressive strength, as the ratio of GPP increases to the extent of 17% then starts to decrease. There is much more difference in the flexural strength values between the early and later ages especially at the content of 17% GPP.

• Bond strength values show similar behaviour as the compressive strength.it increases to the content of 12% of GPP then shows decreases.

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