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Effect of red mud (bauxite residue) as cement replacement on the properties of self-compacting concrete incorporating various fillers

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A B S T R A C T

A huge transformation in the cement and concrete industry needs to be made to reduce the environmental pollution, especially carbon dioxide, in order to take consistent steps towards sustainable development. Concrete production has been increasing in the past decades and this is now one of the biggest concerns of researchers who follow a sustainable development approach. The use of waste materials in concrete production is a proven alternative to reduce the consumption of natural resources. On the other hand, red mud (RM), granite (GP) and marble (MP) waste powders, whose disposal has adverse environmental effects, have become environmental concerns in industrial areas. In light of these issues, employing alternatives to benefit from such valuable local waste materials, rich in silica, alumina, and ferric oxide, can be a great help to the environment. In this study, to evaluate the efficiency of using these materials in self-compacting mixes, the fresh and mechanical parameters were first determined, and then experiments on waste mixes produced with varying percentages of RM (2.5%, 5%, 7.5%, and 10%) as partial replacement of cement, besides using GP and MP as filler replacement (at 100%), were performed. Although application of RM negatively influenced the fresh properties, it was observed that a low level of RM incorporation along with MP and GP enhanced the mechanical properties of self-compacting concrete (SCC), e.g. a mix made with 2.5% of RM and 100% of GP can increase the compressive strength by 19% compared to that of the control mix. Depending on the local characteristics of RM, these conclusions are expected to apply to many locations worldwide.

1. Introduction

Nowadays the construction industry consumes more raw materials and energy than any other economic activity worldwide. One of the most frequent building materials around the world is concrete. Cement, as a basic material of concrete, is manufactured through an energy consuming procedure. Many emissions such as greenhouse gasses are generated in cement production that are responsible for global warming. Cement industry - by producing 5–7% of all CO_2 emissions - is the second highest emitter of all industrial carbon dioxide (He et al., 2019). CO_2 reduction has been investigated by means of using different waste materials as cement replacement. In modern societies, an economical and sustainable way of disposing waste is to apply them as secondary material in the construction industry (de Brito and Silva, 2015).

According to sustainable development goals, the idea of reusing industrial waste and by-products in concrete and mortars production has recently become prevalent (Yao et al., 2013). Chandru et al. (2018) claimed that the addition of industrial by-products at given amounts enhances the rheologic, mechanic and durability properties of concrete. The influence of different types of industrial by-products, like fly ash (FA), silica fume (SF), RM, GP, and MP, has been comprehensively investigated in recent years. GP and MP are widely regarded as mineral additives for SCC production. Re-using local wastes and industrial by-products in concrete production can have benefits from different points of view, since it decreases cement and aggregate consumption. Therefore, an eco-efficient SCC with adequate fresh and hardened state properties can be produced

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using these waste powders (Demirel and Alyamaç, 2018).

1.1. Self-compacting concrete

Recently, SCC has been receiving major attention as a right destiny for waste and by-products that can be used without negative impacts on its fresh and hardened state properties. The key factors in SCC characterization are the efficient filling and passing abilities under its own weight and the stability without sand segregating to achieve full compaction (Naik and Vyawahare, 2013). To assess the behaviour of a Newtonian fluid that is necessary for the required performance, a SCC should have sufficient viscosity and low yield stress (EFNARC, 2005). To achieve these goals, besides using a powerful superplasticizer, a large quantity of fine powder is needed (Ho et al., 2002). Limestone powder (LP), FA and blast furnace slag are regularly used in SCC mixes to maintain the cohesion and segregation resistance (EFNARC, 2005). However, as an eco-efficient alternative, fine powder in SCC mixes could be substituted with waste powder and industrial by-products (Sadek et al., 2016).

1.2. Red mud

RM, a waste substance generated in aluminium plants by the Bayer process, is an alkaline leaching waste (Ribeiro et al., 2011). Worldwide production of RM exceeds 117 million tonnes per year (Gautam and Agrawal, 2017). The chemical and mineralogical composition of RM is highly variable depending on the bauxite source and relevant processes. It normally contains six major oxides, CaO, SiO_2, Fe_2O_3, Al_2O_3, TiO_2 and Na_2O and small contents of various minor elements (Yao et al., 2013). The disposal of RM due to its high alkalinity is environmentally detrimental to water, ground and air of the surrounding areas (Samal et al., 2013). e.g. Fe_2O_3 - which is found in RM - reduces intake of phosphorus into plants (Maroušek et al., 2019). Furthermore, planning for RM dumping lands is not economically efficient (Mahadevan et al., 1996). Nevertheless, RM characteristics qualify it as a beneficial material for use in the construction industry. The high pH of RM makes it compatible with cement and steel reinforcement when used in mortars and concrete (Abdel-Raheem et al., 2017). Containing three mineral compounds such as gismondine, goosecrekite and epistilbite which are zeolites, RM provides pozzolanic properties that contribute to the structural integrity of the concrete matrix (Liu and Poon, 2016b). In other words, the enhancement of compressive strength and internal curing in concrete is imputed to the zeolites in the cement paste (Zaichenko, 2011). In several studies, dried RM in its normal form was used as cement replacement, while others used calcined form and milled RM before incorporating it in concrete mixes. Manfroi et al. (2014) evaluated cementitious composites produced by dried and calcined RM incorporation and reported that it could be used as cement replacement in civil construction. Senff et al. (2014) dealt with the influence of RM on the fresh and hardened state properties of mortars. They found that RM incorporation up to 20% does not adversely affect the properties of mortars. Liu and Poon (2016b) and Tang et al. (2018) investigated the incorporation of RM in SCC as replacement of FA and its impact on the mechanical properties of SCC. Generally, in more advanced curing ages (56 and 90 days), the incorporation of RM in SCC enhances the compressive and tensile splitting strength (Tang et al., 2018).

1.3. Granite and marble waste powder

Every year tonnes of marble and granite waste, one of the environmental threats worldwide today (Lakhani et al., 2014), accumulate. Recently, it has been shown that mineral admixtures can be used in concrete and mortars production leading to an improvement in some fresh and hardened state properties of concrete. In 2016, Arel (2016) replaced 20% and 30% of cement and sand with MP and reported that these amounts could be considered an optimum value for the filler content in SCC. Since LP is ordinarily used as filler material in SCC mixes, Corinaldesi et al. (2010) investigated the potential use of MP as filler material in mortar and concrete mixes. The effects of MP and LP on the mechanical properties of concrete mixes were similarly studied by Binici et al. (2008). They all reported that the application of MP can improve the general characteristics of concrete, due to its finer particle size, and its better grain size distribution. In 2018, Khodabakhshian et al. (2018b) investigated the effect of MP and SF as partial replacement of cement on the mechanical properties of concrete mixes. The results indicated that up to 10% of MP as partial replacement of cement the compressive strength of mixes improves and using both MP and SF in mixes will lead to an optimized mix, when considering environmental, economic and mechanical performance. Similarly, Ergün (2011) reported that 5.0% and 7.5% substitution of cement with waste powder tends to increase the compressive strength of the samples. This enhancement was attributed to the filler effect of MP which fills up the voids between the sand grains (Lakhani et al., 2014).

The incorporation of GP in concrete has also been studied by many researchers. Singh et al. (2016a) showed that using granite cutting waste in concrete production enhanced the mix performance due to its micro filler effect. In 2010, Felix Kala and Partheeban (2010) claimed that 25% of sand partially replaced by GP has beneficial effect on the mechanical properties of high-performance concrete. In another research, it was reported that replacement of natural sand with GP up to 15% does not adversely affect the strength and durability characteristics of concrete (Vijayalakshmi and Sekar, 2013). Allam et al. (2014) experimentally assessed the effect of sand and cement replacement with GP. They observed that sand replacement with GP enhances the 28-days compressive strength of samples, whereas the compressive strength is dramatically decreased in the case of cement replacement. However, researchers in some cases mentioned that a limited amount of GP should be used in concrete mixes, due to its high fineness (Singh et al., 2016a).

GP and MP have been applied as both cement and sand replacement in concrete production. However, using GP and MP as substitution of sand in concrete mixes has been more favourable (Sadek et al., 2016), due to their low pozzolanic potential. According to the experimental program of Binici et al. (2008) and Corinaldesi et al. (2010), MP and GP can be used as sand replacement for a limited amount, without influencing the fresh and hardened state properties. Evaluating the mechanical performance of MP mortar, Corinaldesi et al. (2010) concluded that a mix with 10% of MP as sand replacement and superplasticizer will result in maximum compressive strength. Moreover, Sadek et al. (2016) evaluated the possibility of using MP and GP as mineral additive to SCC. They showed that waste powders could be successfully used in SCC mixes.

2. Methodology

The GP and MP used in this research were brought from Tape Salam, located in the south of Mashhad, Iran. All samples were collected from a specific location at a time. The sampling procedure performed is in accordance with ASTM C311 (2018a). RM is the by-product of Bayer process in an alumina plant in Jajarm, Iran. Portland cement type II with a specific weight of 3200 kg/m^3 according to ASTM C188 (2017a) was used. A polycarbonate-based superplasticizer was used to maintain the stability of the mixes.

2.1. Grain size distribution

Fig. 1 shows the coarse and fine aggregate size distribution used to produce SCC mixes in this research. The grain size distribution of cement, RM, GP and MP also can be seen in Fig. 2 and Fig. 3.

2.2. Mixes design

Series A has a proportion of 2.5%, 5%, 7.5%, and 10% of cement weight replaced with RM. Similar to the control mix, LP was used as a filler in this series. In series B, the filler material is substituted by GP, and the amount of RM is similar to that of series A. Series C mixes also included similar schemes to series B, except for MP that was used as filler. The mix design was carried out using the standard volumetric method of ACI 211.1 (1991). Table 1 presents the details of the mixing proportions, where the water to cement ratio was equal to 0.46 and the content of superplasticizer was 300 kg/m^3.

Table 2 illustrates all the references used to determine the fresh and hardened state properties of the concrete mixes.

3. Results and discussion

3.1. Slump and T500 time tests

In this research, the “slump flow” and the “T_{500} time” tests were performed to measure the flowability characteristics and the consistency of fresh SCC. The slump test was based on the related test described in ASTM C1611 (2018) (see Fig. 4). Additionally, the speed of the flow and viscosity of SCC were evaluated by the T_{500} test. As seen in Table 3 and Fig. 5, the slump flow diameter (SFD) values for all mixes were between 58 and 70 cm. Moreover, the results of T_{500} time test are shown in Table 3 and Fig. 6 . By increasing the RM content, a corresponding reduction of workability was observed, which is in agreement with the results obtained by Tang et al. (2018). They reported that, when using more RM as cement replacement, adverse effects on the fresh properties of concrete are inevitable. Also, this result was reported for mortars containing RM or same natural zeolite (Ahmadi and Shekarchi, 2010; Liu and Poon, 2016a, b; Senff et al., 2014). The reduced workability of concrete with RM was mainly attributed to the large surface area and high porosity of RM particles (Ahmadi and Shekarchi, 2010; Senff et al., 2014). In fact, in comparison with cement, the larger surface area of RM particles caused an increase in water demand of the mixes.

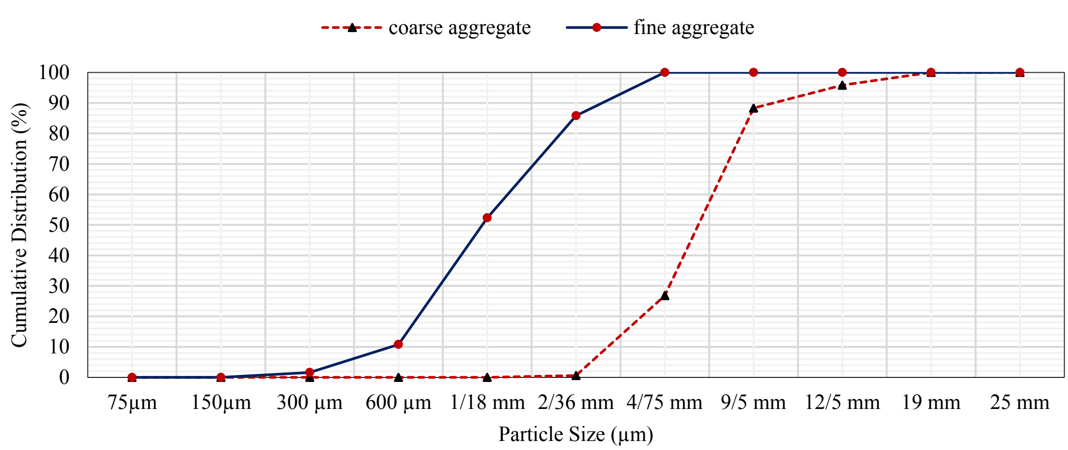


Fig. 1. Grain size distribution of the coarse and fine aggregates.

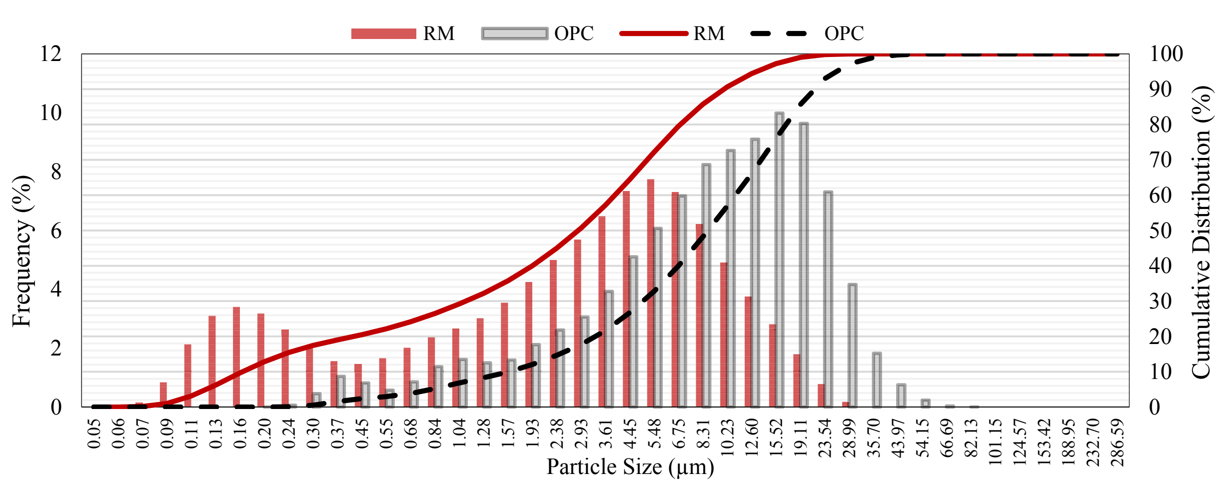


Fig. 2. Grain size distribution of the cement and RM.

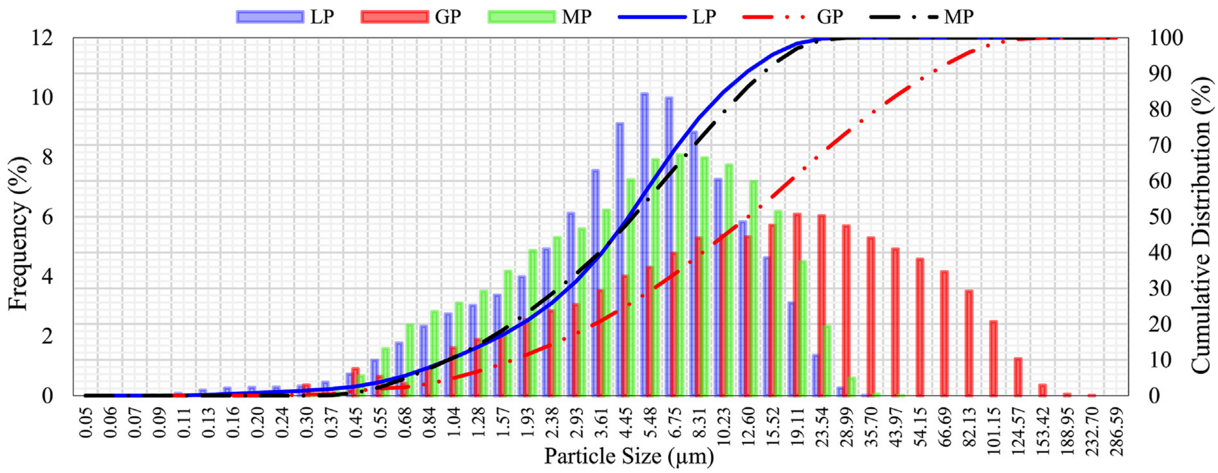


Fig. 3. Grain size distribution of the LP, GP and MP waste powder.

Table 1
Mix proportions.

Cont.		Concrete mixes	W[a] (kg/m^3)	C[b] (kg/m^3)	LP[c] (kg/m^3)	GP (kg/m^3)	MP (kg/m^3)	RM (kg/m^3)	FA[d] (kg/m^3)	CA[e] (kg/m^3)	SP[f] (kg/m^3)
		LP-RM0	183.5	400	100	0	0	0	975	525	7
A	1	**LP-RM2.5**	183.5	390	100	0	0	10	975	525	7
	2	**LP-RM5**	183.5	380	100	0	0	20	975	525	7
	3	**LP-RM7.5**	183.5	370	100	0	0	30	975	525	7
	4	**LP-RM10**	183.5	360	100	0	0	40	975	525	7
B	5	**GP-RM2.5**	183.5	390	0	100	0	10	975	525	7
	6	**GP-RM5**	183.5	380	0	100	0	20	975	525	7
	7	**GP-RM7.5**	183.5	370	0	100	0	30	975	525	7
	8	**GP-RM10**	183.5	360	0	100	0	40	975	525	7
C	9	**MP-RM2.5**	183.5	390	0	0	100	10	975	525	7
	10	**MP-RM5**	183.5	380	0	0	100	20	975	525	7
	11	**MP-RM7.5**	183.5	370	0	0	100	30	975	525	7
	12	**MP-RM10**	183.5	360	0	0	100	40	975	525	7

[a] Water.
[b] Cement.
[c] Limestone Powder.
[d] Fine Aggregate.
[e] Coarse Aggregate.
[f] Super Plasticizer.

Since the water amount is constant in all mixes, higher viscosity and lower workability resulted.

For small RM contents (2.5% as cement replacement), a reduction of workability was observed in series A and B, while using MP as filler material enhanced it. The results of Gesoğlu et al. (2012) showed that the use of LP in SCC increases the need of superplasticizer to keep the slump flow diameter constant. They also reported that incorporating GP as filler rises the superplasticizer demand due to the high fineness of the GP particles compared to that of cement. In 2016, Singh et al. (2016b) reported that higher amounts of GP in concrete lead to higher viscosity of the mix, resulting in slump reduction. Physical properties of fine aggregates such as particle size, shape, distribution and texture affect workability. LP and GP particles with irregular shapes and high fineness increased the contact between particles and made the mix denser (Singh et al., 2016b). In addition, increasing the waste powder led to an increase in water demand as reported by Demirel and Alyamaç (2018), due to finer and rougher particles of waste materials such as GP (Vijayalakshmi and Sekar, 2013). The possibility of using MP as filler material was also investigated by Gesoğlu et al. (2012) and it was shown that its adverse influence on the fresh properties of SCC can be mitigated by using superplasticizer. To meet the SCC requirements, it has been suggested that more superplasticizer is needed in SCC mixes with waste powders like RM, GP or MP (Liu and Poon, 2016b).

Table 2
Tests and standards used in this research.

Tests	Standards
Slump and T500 time tests	ASTM C1611(2018)
L-box test	Petersson et al. (2004)
V-funnel test	Ozawa et al. (1994)
Compressive strength test	BS EN12390-3 (2009)
Tensile strength test	ASTM C496 (2017)
Water absorption	ASTM C642 (2013)
Electrical resistivity	Khodabakhshian et al. (2018a)
Ultrasound pulse velocity test	ASTM C597 (2016)
Durability against sulfuric acid attack	ASTM C267 (2012)

3.2. L-box and V-funnel tests

The L-box test is normally used to assess the rheological behaviour of concrete and its capacity to stay homogeneous. In accordance to the European guidelines for SCC, the L-box test is measured by the h_2/h_1 ratio (see Fig. 7). For optimal workability level, h_2/h_1 is equal to 1 and decreasing concrete workability is

Control mix A3 mix B3 mix

Fig. 4. Slump test.

Table 3
Slump and T_{500} values.

Concrete mix	Slump index (mm)			T_{500} time (sec)
	First diameter	Second diameter	Mean value of diameter	
control	660	660	660	5.4
A1	650	650	650	5.5
A2	640	650	645	6.1
A3	640	630	635	6.6
A4	620	630	620	7.1
B1	620	610	615	7.1
B2	580	610	595	7.9
B3	560	620	590	8.4
B4	580	590	585	8.9
C1	690	700	695	3.0
C2	660	700	680	3.2
C3	660	640	650	4.5
C4	630	640	625	4.9

measured by the reduction of this index. The results in Fig. 8 indicate that replacing cement with RM decreased the L-box ratio. Liu and Poon (2016b) reported the same result as more FA replaced with RM in SCC mixes, considering that RM particles are larger than FA and smaller than cement grains. Using 2.5% of RM, the L-box ratio decreased by 1%, 5% and 2%, respectively, when LP, GP and MP were used as filler material. These reductions were equal to 4%, 11% and 7% for 10% of cement replacement with RM as LP, GP and MP filler, respectively. In fact, more viscosity of the SCC mix was observed by using high fineness powders. Nevertheless, according to the European guidelines for SCC (EFNARC, 2005), all of the L-box values were within the acceptable range.

To evaluate the deformability of fresh SCC, the V-funnel test should be used in addition to the slump flow test (Khayat, 1999). The V-funnel test was proposed by Ozawa et al. (1994) in order to examine the flowability and viscosity of concrete with a maximum aggregate size of 20 *mm* by measuring the time taken for 12 *L*of concrete to flow through the gate of the V-shaped funnel. The maximum acceptable time duration for SCC to flow is 12 sec (EFNARC, 2005).

Fig. 9 illustrates the results for all mixes in this study. Using RM as cement replacement, increased the time duration for fresh concrete to completely pass through the gate. The results also revealed that, in comparison with mix A1, the V-funnel time increased by 17.5% (series B) and decreased by 10% (series C). In fact, LP and GP as filler increased the time needed for the mix to pass through the funnel, while MP decreased this time.

None of the mixes met the acceptance criteria in accordance with European guidelines for SCC (EFNARC, 2005). As more RM was used in SCC, a more intense reduction trend in the results was observed and the V-funnel time increased. Liu and Poon (2016b) reported the same outcome. Two major reasons explained the high V-funnel time and greater viscosity of the mixes. First, the finer particles of RM compared to cement increased the paste volume as its ratio in the mix increased. Second, the fineness of RM particles enhanced the surface area of the paste and increased water demand. More paste volume along with fixed water to cement ratio led to a viscous mix. Gesoğlu et al. (2012) investigated the possibility of MP utilization in SCC. Finer size distribution of MP grains resulted in a decrease in V-funnel test time compared to that of the control mix. 10% of cement replacement with RM in the presence of angular and rough components of GP resulted in the highest V-funnel time. Compared to other natural waste powders, granite's increases the viscosity and V-funnel time (Hunger and Brouwers, 2008). Moreover, the application of LP as filler in SCC increased the flow time and this resulted in a more viscous mix (Bosiljkov, 2003). Fig. 10 indicates the correlation between L-box ratio and V-funnel time with $R^2 = 0.56$. The correlation between

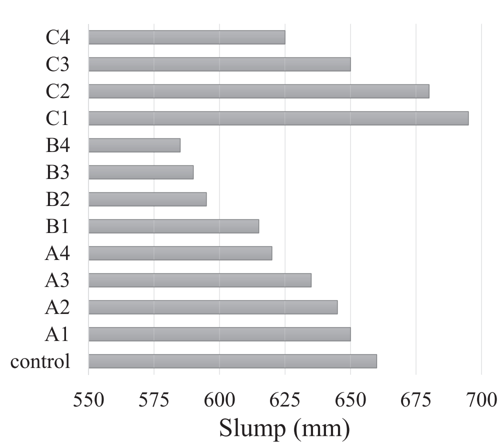


Fig. 5. Slump test values.

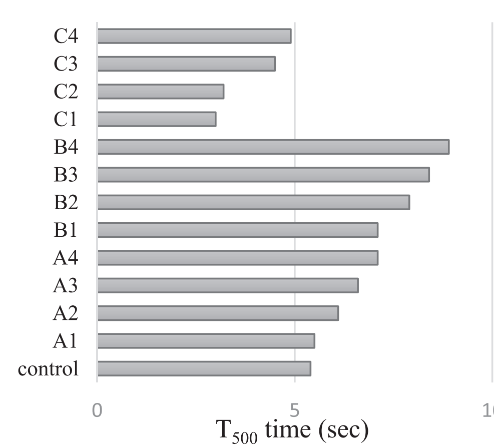


Fig. 6. T_{500} test values.

Fig. 7. L-box test of B4 sample before and after opening the gate.

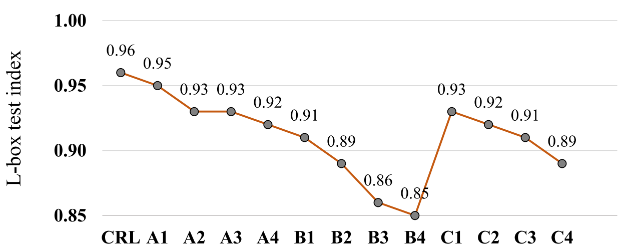


Fig. 8. L-box test values.

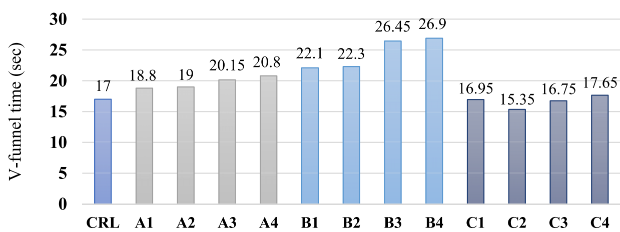


Fig. 9. V-funnel test values.

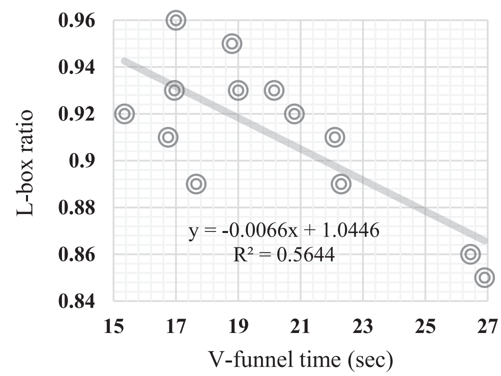


Fig. 10. Correlation between V-funnel time and L-box ratio.

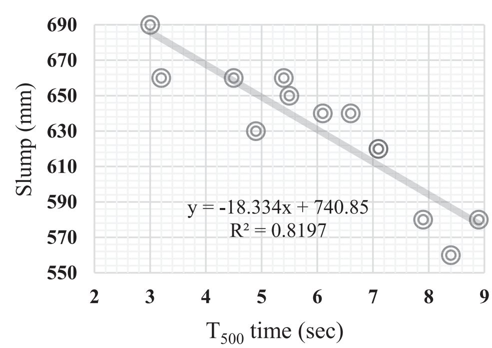


Fig. 11. Correlation between T_{500} time and slump value.

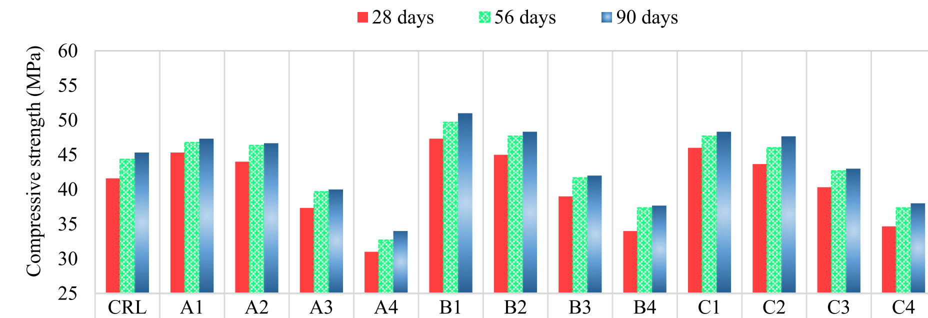
T_{500} time and slump values is also shown in Fig. 11. In this research, a low level of RM incorporation along with MP as filler and use of superplasticizer resulted in the best workability properties.

3.3. Compressive strength test

The compressive strength test was performed on 100 × 100 mm cubic specimens at 28, 56 and 90 days of curing. The specimens were loaded to failure in a compression testing machine conforming to BS EN 12390-4 (2000). The results are shown in Fig. 12.

All series showed a relatively similar behaviour when the RM content increased, at all ages. Generally, limited RM content (up to 2.5%) as cement replacement led to an increase of the compressive strength of all series relative to that of the control mix, which is in agreement with the results of Kushwaha et al. (2013) and Shetty et al. (2014), reporting an optimum value of 2% for cement replacement. In 2018, Tang et al. (2018) measured the optimum RM content instead of FA in SCC mixes, and explained that the internal curing of the zeolite mineral compounds of RM (Liu and Poon, 2016b) may enhance the compressive strength of the mixes, particularly at more advanced ages. However, as the RM incorporation ratio increased (more than 2.5%), the compressive strength decreased, similarly to the results reported by Liu and Poon (2016b). Evaluating RM mortars, Ortega et al. (2019) also reported that the compressive strength of mortars at 28 days decreases when RM content exceeds 10%. In fact, it was reported that RM has a low pozzolanic reaction compared to that of cement, restricting high contents of RM in the construction industry as cement replacement (Ribeiro et al., 2011; Senff et al., 2014). However, using RM at low level of cement replacement in concrete mixes could be effective in terms of compressive strength (Liu and Poon, 2016b), as the high fineness of RM particles and its filler effect can densify the matrix of concrete (Ribeiro et al., 2011).

Regarding the filler replacement, all mixes containing GP and MP had better performances in terms of compressive strength compared to their counterparts in series made with LP. For example, mixes containing B1 and C1, made with 2.5% RM, had a compressive strength of about 51 and 48 *MPa*at 90 days, while mix A1 showed a compressive strength of approximately 47 *MPa*, at the same curing age. Mixes containing GP and MP with the highest content of RM (10%) also showed better results compared with mix



	CRL	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
28 days	41.6	45.3	44.0	37.3	31.0	47.3	45.0	39.0	34.0	46.0	43.7	40.3	34.7
56 days	44.3	46.8	46.3	39.7	32.7	49.7	47.7	41.7	37.3	47.7	46.0	42.7	37.3
90 days	45.3	47.3	46.7	40.0	34.0	51.0	48.3	42.0	37.7	48.3	47.7	43.0	38.0

Fig. 12. Compressive strength at 28, 56 and 90 days.

A4 (made with LP as filler) when testing compressive strength, with 34, 37.6, and 38 *MPa* for mixes A4, B4, and C4, respectively, after 90 days of curing. The slight increase in the series containing GP can be explained by its low pozzolanic activity (Asadi Shamsabadi et al., 2018), as it contains a high volume of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3), while these minerals can only be found in lower volumes in LP and MP. In addition, investigating the particle size distribution of GP, MP, and LP, more than 90% of GP particles were within the range of 1–82 μm, whereas these range was 0.68–15 μm for both MP and LP. This particle size range that contained just above 50% of GP particles was 4.5–31μm, while it was 2.4–9 μm and 2.4–8 μm for MP and LP, respectively. These results show that the extended particle size distribution of filler can help concrete to be more homogenous, resulting in a slight increase in the mechanical properties. Benjeddou et al. (2017) reported that increasing the fineness of the filler adversely affects self-compacting behaviour of the SCC in a way that might stop self-compactability. Accordingly, the mixes made with GP experienced an increase in compressive strength compared to the control mix and their counterparts in series A and C. Also, the series made with MP (C), with a very similar particle size distribution and chemical composition to that of LP, showed an approximately similar behaviour to that of series A.

The results obtained in this study were compared with those of Kushwaha et al. (2013) and Shetty et al. (2014), which are shown in Fig. 13. The comparison shows that in all the three studies the behaviour of concrete when the RM content (as cement replacement) increased were similar, as mixes made with 2–2.5% RM showed the best performance. Moreover, increasing the replacement ratio up to 5% resulted in compressive strength values approximately similar to that of the control mixes.

3.4. Tensile strength test

Tensile strength of the specimens, which is discussed in this part, plays a very important role in analysis of concrete structures using finite elements, in addition to compressive strength (Yousefi and Ghalehnovi, 2018). Several factors may influence the tensile capacity of concrete, including type of aggregate and size distribution of the aggregate particles, water to cement ratio, number and size of voids in the paste, and bond between binder and aggregates. In general, the tensile strength depends on the strength of the matrix and on the adhesion (bond) of the hardened cement paste to the aggregate particles. Low strength hardened cement paste and poor interfacial transition zone (ITZ), which are results of a high volume of water compared to the cement content, decrease the tensile capacity of concrete. In addition, the number and size of voids, including capillary pores, air voids, or micro-cracks, in the paste that largely influence the tensile strength can be linearly related with W/C ratio. Normally, higher W/C ratios produce a more porous concrete with larger pores. Moreover, the ITZ, which can be negatively affected by calcium hydroxide crystals on the surface of the aggregate particles, determines the bond between the cement paste and aggregates (Reinhardt, 2013).

The splitting tensile strength of the specimens at the age of 28 and 56 days was tested, and the results are shown in Fig. 14. A low

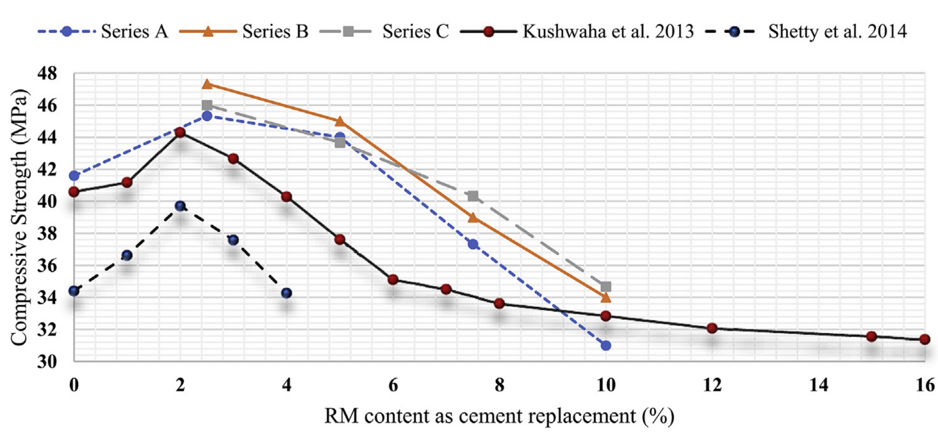


Fig. 13. Compressive strength at 28 days for different levels of cement replacement.

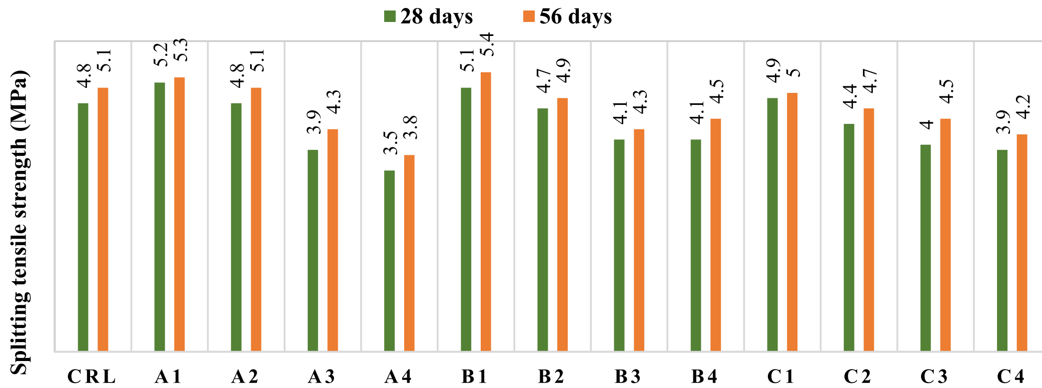


Fig. 14. Splitting tensile strength at 28 and 56 days.

content of RM (2.5%) instead of cement, in the presence of LP as filler, increased the tensile strength of samples by respectively 8% and 4% at 28 and 56 days, and the application of GP and MP did not significantly change the tensile behaviour of the specimens. By adding more RM to the mixes in all series (A, B and C), the splitting tensile strength slightly decreased, and mix A4 experienced the maximum decrease of 1.3 MPa at both 28 and 56 days. As shown in Fig. 14, there was a slight difference between the tensile strength of samples at curing ages of 28 and 56 days. In this study, the optimum level of cement replacement was 2.5% with the highest positive effect on tensile strength in all series. Also, in series A, made with LP, mix A2, containing 5% of RM, showed a similar performance to the control mix. Overall, in this study, the slight improvements in tensile strength can be related with the lower porosity and improved properties of the binder and the interfacial transition zone (ITZ), as mentioned by Aliabdo et al. (2014). The smaller size of RM particles (median diameter of about 2.86μm) compared with cement particles (median diameter of about 8.65μm) makes them capable of improving the densification of the ITZ and consequently the splitting tensile strength.

In addition, as mentioned in the previous section, the internal curing of the RM might be the reason for the tensile strength development at higher curing ages (Rana et al., 2015). Moreover, Lakhani et al. (2014) found that stone waste as sand replacement could increase the tensile strength due to a filler effect. In 2014, Aliabdo et al. (2014) also reported that MP as cement addition positively affected the tensile strength of concrete.

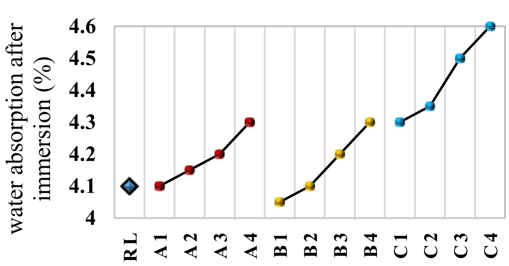


Fig. 15. Water absorption.

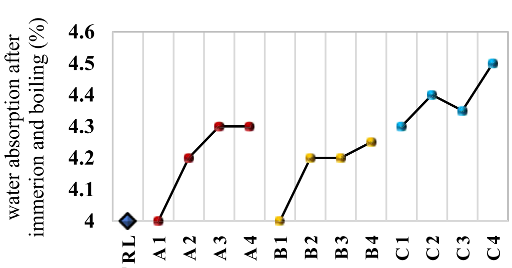


Fig. 16. Water absorption after boiling.

3.5. Water absorption and water absorption after boiling tests

According to ASTM C642 (2013), the water absorption of all specimens at 28 days was tested, considering the size of the samples that should not be less than 350 cm^2 and the specimens that should be without any cracks or fractures on the edges. The results of this test are shown in Figs. 15 and 16. GP did not change the water absorption of the specimens, while MP slightly increased this property, and mix C4 showed the maximum water absorption value. In addition, increasing the RM content had a negative effect on the water absorption of SCC, due to the presence of many "pits" and "folds" on the surface of the RM particles, and subsequently the capacity of absorbing water increased (Liu and Poon, 2016b). Regarding the behaviour of the specimens in terms of water absorption after boiling, the general trend was similar to the results of water absorption after 24 h immersion. Overall, it can be said that the capacity of concrete to absorb water increased when the RM ratio enhanced. However, mixes A1 and B1 made with 2.5% RM showed similar behaviour to that of the control mix.

3.6. Electrical resistivity (ER)

The ER test was applied according to the method proposed by Khodabakhshian et al. (2018a). Three $100 \times 200mm$ cylindrical specimens for each mix were tested at a voltage of 30 V, at 28 days.

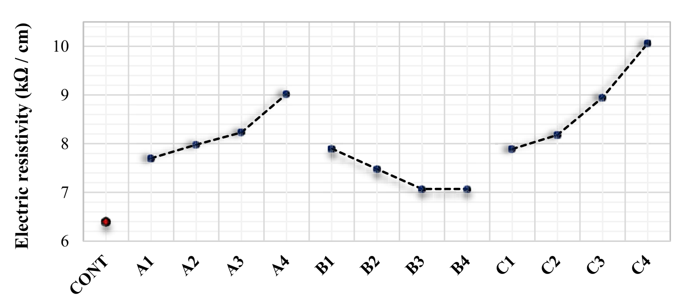


Fig. 17. Electrical resistivity.

All the results are shown in Fig. 17. Overall, the capacity of concrete to remain unharmed by the transfer of ions targeted by an electric force can be considered as the electrical resistivity. Within this framework, pore interconnections can be studied using the ER test. The electrical resistivity that somehow quantifies the conductive properties of the concrete microstructure can be a strong representative of some durability properties, including chloride diffusion coefficient, water absorption, and corrosion rate of reinforced concrete (Layssi et al., 2015).

Fig. 17 shows that, with the incorporation of RM, the ER of mixes of series B slightly decreased, limited to $1 k\Omega/cm$, with the increase in RM content, while two other series experienced upward trends. This result can be related with the finer size of RM particles and the internal curing effect of RM. It was also concluded that using GP and MP as filler material increases the ER, as mixes made with GP and MP experienced higher ER than their counterparts in series A. However, mix B4 showed the minimum ER (around $7 k\Omega/cm$), while mix C4 showed the maximum ER at about $10 k\Omega/cm$. It is worth noting that the values obtained for all mixes were higher than that of the control mix ($6.40 k\Omega/cm$).

There are two main groups of factors influencing the electrical conductivity of concrete: (1) intrinsic factors such as water to cement ratio, age of the specimens, size and connections of voids, type and size of aggregates, and the hydration process; (2) factors affecting the resistivity measurements, including specimen geometry, moisture content, temperature, electrode spacing, and the presence of rebars (Layssi et al., 2015). Khodabakhshian et al. (2018a) reported slightly lower ER of normal mixes containing MP as cement replacement with a greater particle median diameter than RM, while Gesoğlu et al. (2012) reported that the incorporation of MP up to 20% in SCC increased the ER values of the specimens. In both cases, MP was used as cement replacement, but the results are completely different, highlighting the role of several factors on the ER. In this study, series containing GP, which had a very different chemical composition and particle size distribution compared with LP and MP, showed a different trend when increasing the content of RM, which can be related with the mentioned differences.

As mentioned earlier, the ER is representative of the durability properties, as it is a function of pore size distribution and interconnections. Fig. 18 shows the correlation between ER and water absorption. Generally, there is a strong relationship between ER and water absorption of concrete specimens as reported in previous studies (De Medeiros-Junior et al., 2019; Khodabakhshian et al., 2018a) and as they are shown for each series in the figure. However, the correlation between ER and water absorption results obtained for all mixes in this study cannot be considered strong, but acceptable. The different trend of ER results in series B, which decreased when the RM content increased, is the reason behind the correlation coefficient of about 0.5 when considering all mixes.

3.7. Ultrasound pulse velocity test

This test method covers the determination of the propagation velocity of longitudinal stress wave pulses through concrete. An electro-acoustical transducer in contact with one surface of concrete was used to generate the pulses of longitudinal stress waves. The pulses received on the other surface of the specimen were converted into electrical energy by a second transducer. The pulse velocity V was calculated by dividing L (the distance between the two transducers) by T (transition time). The schematic of ultrasound pulse velocity test is seen in Fig. 19.

By relating the ultrasound pulse velocity (UPV) with the compressive strength of SCC samples, a positive correlation was observed, similarly to Rodrigues et al. (2015). In Fig. 20, a slight decreasing trend was observed by increasing the RM content in all three series. Türkmen et al. (2010) replaced cement with various percentages of natural zeolite in SCC mixes and reported that natural zeolite reduces the compressive strength and ultrasound pulse velocity. RM consists of high amounts of zeolite (Liu and Poon, 2016b) and, as Türkmen et al. (2010) claimed, natural zeolite decreases the heat of hydration of concrete and that is why the ultrasound pulse velocity decreased as the RM content in SCC increased. Using GP and MP as filler material did not adversely affect the ultrasound pulse velocity. Mix C1 made with MP as filler and the lowest RM content showed the highest ultrasound pulse velocity of about 4700 m/s, while mix B4 containing GP and a high content of RM showed the lowest pulse velocity (4162 m/s).

3.8. Durability against sulfuric acid attack

The compressive strength of the specimens was determined after 28 days in 5% sulfuric acid solution and the results were compared with those of samples cured in tap water. The results are shown in Fig. 21. The control mix with 9% reduction in compressive strength exhibited the highest durability against sulfuric acid attack while mix B4 with a 22% reduction in compressive strength showed the lowest resistance against sulfuric acid attack. Mineral additives incorporation, depending on the size, shape and texture of their particles, affected concrete durability against sulfuric acid attack in a positive manner or vice versa.

Using LP had two major benefits for the mixes: (1) the increase in chemical reaction between LP and sulfuric acid that neutralized acid surrounding concrete (Chang et al., 2005); (2) the high

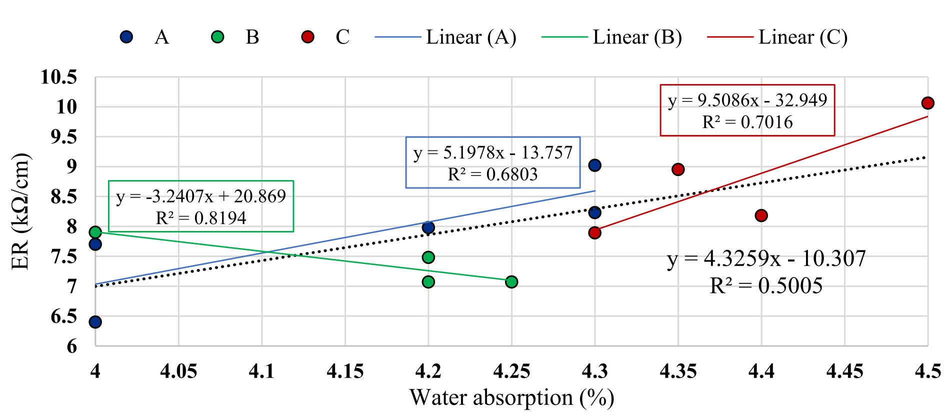


Fig. 18. Correlation between ER and water absorption.

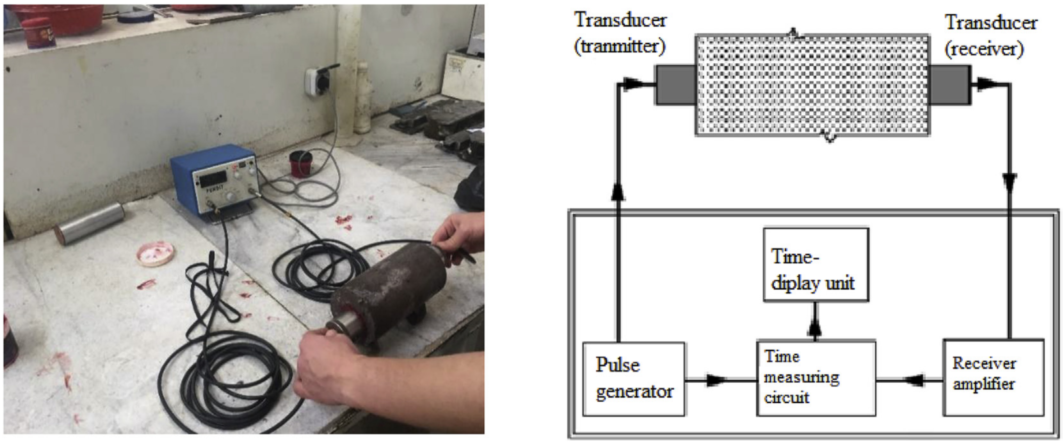


Fig. 19. Schematic representation of the ultrasound pulse velocity test.

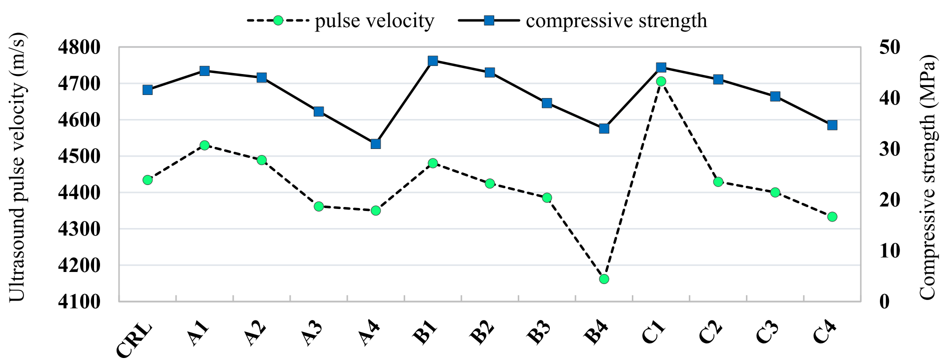


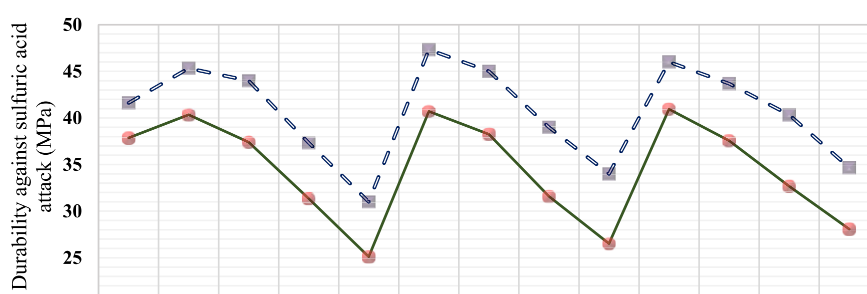
Fig. 20. Ultrasound pulse velocity (UPV) and compressive strength.

fineness of its particles can decrease the porosity of concrete (Cizer et al., 2011) and, as a result, a denser microstructure was produced which may prolong the initiation time before sulfuric attack in SCC (Bassuoni et al., 2007). In fact, calcium carbonate in LP developed the locally buffer effect against sulfuric acid attack and increased the resistance of mixes in adverse conditions (Bassuoni et al., 2007). Khodabakhshian et al. (2018a) also investigated the effect of MP filler in concrete mixes and reported that the main effect of MP on the durability of concrete against sulfuric acid can be attributed to the physical nature of the fine MP particles.

However, by increasing the RM content, concrete durability decreased against sulfuric acid attack. Fig. 22 shows that using RM at 2.5%, 5%, 7.5% and 10%, in series B, caused a reduction in compressive strength by 14%, 15%, 19% and 20%, respectively. In series C, the compressive strength decreased by around 11%, 14%, 19% and 19% by substituting 2.5%, 5%, 7.5% and 10% cement for RM. In 2018, Choudhary et al. (2018) explained that porous materials such as RM have higher voids which may lower the durability of the mix.

4. Conclusion

Regarding the fresh and mechanical properties of SCC, 12 mixes containing LP, MP, GP (as filler replacement), and RM (as partial



	CRL	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
immersed in water	41.60	45.33	44.00	37.33	31.00	47.33	45.00	39.00	34.00	46.00	43.67	40.33	34.67
immersed in acid	37.86	40.34	37.40	31.36	25.11	40.70	38.25	31.59	26.52	40.94	37.56	32.67	28.08

Fig. 21. Durability against sulfuric acid attack.

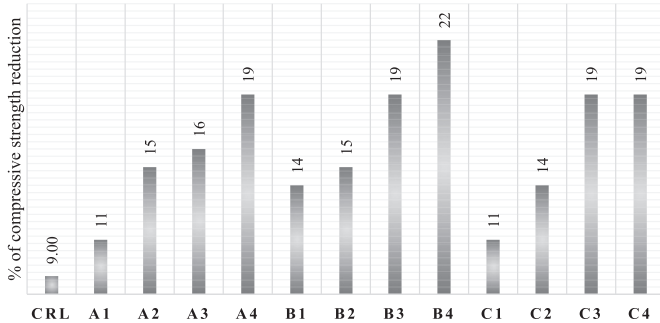


Fig. 22. Loss of compressive strength.

cement replacement) were determined. Slump flow diameter, T_{500}, L-box and V-funnel test results showed undesirable performance by using greater RM content. Hardened specimens were tested for compressive and tensile strength, electrical resistivity, water absorption, ultrasound pulse velocity, and durability against sulfuric acid and it was found that low levels of cement replacement ratio did not adversely affect SCC. In more detailed form, the following conclusions were drawn:

- ❖ The larger specific surface area of RM besides the high porosity of its particles compared with cement cause the fresh properties to degrade. Even small amounts of replacement will reduce the free water in the concrete mix and, as a result, increase its viscosity and reduce its slump flow;
- ❖ Generally, the application of waste materials as filler in SCC mixes changes the behaviour of concrete in different ways. Actually, the performance of concrete containing waste powder materials directly depends on the physical and chemical characteristics of the target waste, and the type of replacement. For example, in this study, using GP and MP instead of LP (filler) respectively increased and decreased the T_{500} time test values, while the application of RM as cement replacement increased these test values;
- ❖ Increasing the content of RM reduced the compressive strength of concrete at all ages, highlighting the low cementitious properties of RM. However, the use of RM up to 2.5% increased the compressive strength, which may be attributed to the internal curing and filler effects of RM. By adding up to 5%, the compressive strength was reduced to values similar to that of the control mix. Overall, the application of 2.5% RM as cement replacement with GP and MP as filler material, increased the compressive strength by up to 19% and 16%, respectively. It is worth noting that using MP and GP instead of LP as filler material has a significant effect on compressive strength;
- ❖ Up to 2.5% of cement substitution with RM, the splitting tensile strength increased before experiencing a downward trend by further increasing the content of RM. In series made with LP as filler, the tensile splitting strength of SCC mixes made with 2.5% RM increased by about 8% relative to the control mix;
- ❖ Using MP instead of LP increased water absorption by up to about 19%, with the highest adsorption rate for a sample with 10% RM, while the application of GP did not change the performance of the specimens. The application of RM also increased the water absorption of SCC, mainly because of the pits and folds on the surface of RM grains;
- ❖ The comparison of the performance of all series in terms of resistance against sulfuric acid attack shows that the application of MP or GP instead of LP in SCC mixes has no significant effect on this property. However, replacing cement with RM and increasing its content reduces concrete's durability;
- ❖ Overall, comparing all fillers used in this study in terms of rheological properties, MP was the best filler, while both GP and MP could increase the mechanical properties of concrete and had relatively similar performances. Regarding the application of RM as cement replacement, although using RM in small amounts (2–5%) can result in a slight enhancement of the mechanical properties, it would significantly degrade the rheological properties. In addition, using large amounts of RM in concrete production, particularly as cement replacement, can significantly decrease the overall performance.

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