Journal of Scientific & Industrial Research
Vol. 83, April 2024, pp. 445-452
DOI: 10.56042/jsir.v83i4.2679

Experimental Investigation on the Effects of Recycled Pavement Materials on the Performance of Self-Compacting Concrete

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Received 15 June 2023; revised 18 January 2024; accepted 16 February 2024

Development and research of new compositions of Self-Compacting Concrete (SCC) based on Recycled Aggregates (RA) and Recycled Pavement (RP) are primary objectives for builders. These aggregates must be suitable to produce an SCC with properties acceptable for short and long term. This study presents experimental work focusing on the properties of SCC obtained by the addition of 15%, 30% and 45% of RP to the Natural Aggregates (NA), both in the fresh and hardened states, such as slump flow, T_{500} spread time, V-funnel flow time in the fresh state, Flexural Strength (Sf), Compressive Strength (Sc), Sorptivity (S), Water Absorption (WA) and Porosity (P) in the hardened state. These properties have been investigated and analysed in detail. The results indicate that the use of NA with that of RP up to 30% retains almost the same properties of the SCC. Moreover, the relationship-based equations that express the variation of Sc and other parameters give fair correlation coefficients, which are close to the value of one. Consequently, it is recommended to use RP with well-determined quantities for manufacturing better SCC, which allows the recovery, recycling and valorization of large quantities of RP.

Keywords: Cement, Compressive strength, Natural aggregate, Sorptivity, Workability

Introduction

Today, Concrete is required to meet increasing standards in terms of mechanical, durability performance, workability, environment and appearance. Numerous researchers in materials and civil engineering are working to develop and test new and more efficient materials.[1]

Concrete is the most used material in construction particularly in building and infrastructure projects. Its rapid construction speed, mechanical strength, and durability have led manufacturers to utilise it in various structures such as offices, residential buildings, bridges, power plants, and pavements. Following the pursuit of improved strength and durability, significant advancement shave been made with Self-Compacting Concrete (SCC).

Self-compacting concrete has a wide range of applications, with strengths ranging from Ordinary Concrete (OC) to high-performance concrete, from housing to civil engineering structures. Self-compacting concrete is characterized by its exceptional fluidity, allowing it to be placed into form work without requiring vibration.[2,3] This feature of SCC represents a significant shift and evolution in concrete construction. Its fluidity and deformability enable it to settle and compact under its own weight, eliminating the need for external compaction energy. This property allows SCC to conform perfectly to the shapes of even the most intricate form work, facilitating the complex shapes or structures with high-density reinforcement, often resulting in surfaces of superior quality.

The properties of S, P, and WA are generally easily changed, which induces modifications in the microstructure of concrete.[4]

Concrete is classified as SCC when the final material meets specific requirements in its fresh state. Therefore, its formulation must include at least a chemical adjuvant and a mineral addition to ensure workability and stability.

Aggregates containing coated bituminous waste are deemed acceptable for use as inert waste.[5] Utilizing RP in Roller Compacted Concrete (RCC) offers several benefits, including waste reduction, pollution mitigation, preservation of NA, cost reduction, and decreased aggregate usage.

Self-compacting concrete facilitates filling confined sections and congested areas without requiring

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mechanical reinforcement or experiencing material separation.[6] New research studies on the addition of RA in roller compacted concrete have been reported by some manufacturers.[7–9] However, SCC and RCC are primarily tested using RP, made with various sizes and shapes of aggregates.[10–12]

Recycling demolition waste as coarse and fine aggregate in asphalt mixtures is suitable for applications in hot and dry climates. RA exhibits sensitivity to lower temperatures, whereas RP is sensitive to water resistance.[13] The mechanical properties of concrete made with RA are generally reduced, although in some cases, RA concrete exhibits similar Sc to that of NA concrete.[14] Guo *et al.* have reported in their study an increase in drying shrinkage of SCC containing RA.[15] The RA negatively affects the fresh state of the concrete due to its angular shape, roughness and its higher WA. Mathias *et al.* have found that the high WA quantity of the RA has remarkable effect on the mixing water there by affecting the workability of the concrete[16]. On the other hand, the RA is an excellent material for use in unbound pavement layers as its properties positively enhance strength values, especially in the long term.[17]

From an environmental stand point, using RA like the waste brick powder and marble powder in SCC reduces CO_2 emissions in nature.[18,19]

However, there is limited research on the properties of SCC made with RP. This work focuses on formulating and evaluating SCC using pavement waste as RP and comparing its performance with ordinary SCC (without RP) in both its fresh and hardened states.

Experimental Investigation

Materials used

The cement used is ordinary Portland cement type CEM I 42.5 N, with a density of 3100 kg/m^3. It was used for all mixtures. Two types of RA (3/8 and 8/15) from old RP are used for SCC concrete mixtures. The granularities of the materials used such as the sand NA and RP are presented in Fig. 1.

Four mixtures were prepared. The NA was replaced by 0% (reference), 15%, 30% and 45% of RP with a density of 2.10 g/cm^3. A polycarboxylate based super plasticizer (SP) was used with a fixed dosage of 1.5% and which had a specific density of 1.05. Table 1 shows the details of mixtures.

Identification of mixtures: four concrete mixtures were made. The NA was partially replaced by 0%, 15%, 30% and 45% of RP:

- SCC$_0$: with 100% NA (reference concrete).
- SCC$_{15}$: containing 85% of NA and 15% of (RP).
- SCC$_{30}$: containing 70% of NA and 30% of (RP).
- SCC$_{45}$: containing 55% of NA and 45% of (RP).

Test Procedures

Fresh Properties of SCC

In the present work, the filling ability and deformability of SCC were determined using various workability tests. All tests procedures including slump flow, T$_{500}$ spread time and V-funnel flow time were conducted following the European guidelines for SCC.

Hardened Properties of SCC

Mechanical Strength

The Sc test was carried out on cubic specimens; 10 × 10 × 10 cm^3 and was tested according to NF P 18-406. The S_f test was carried out on specimens with dimensions 7 × 7 × 28 cm^3. The SCC specimens were cast in steel molds and covered with a plastic sheet. After 24 h, the SCC samples were demoded and then submerged in water at 20°C until the testing age of 2, 7, 28 and 90 days. They were placed in a flexural by

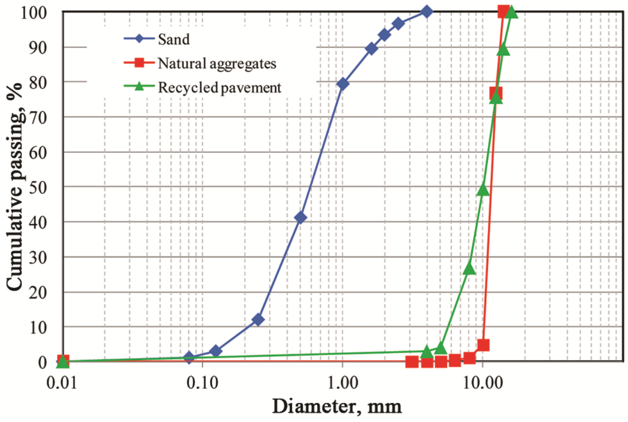

Fig. 1 — Grading curves of the sand the NA and RP

Table 1 — Details of differents mix proportions for SCC

Composition (kg/m^3)	Designation of SCC			
	SCC$_0$	SCC$_{15}$	SCC$_{30}$	SCC$_{45}$
RP 8/15	—	72.99	145.8	218.7
RP 3/8	—	36.48	72.9	109.44
Gravel 8/15	486.6	413.61	340.8	267.9
Gravel 3/15	243.3	206.82	170.4	133.86
Sand	792.6	792.6	792.6	792.6
Cement	427.5	427.5	427.5	427.5
Superplastized	3.84	3.84	3.84	3.84
Water	190.17	190.17	190.17	190.17
Absorption rate of RP	2.08%			
Absorption rate of NA	0.97%			

bending and compressive testing machine under the maximum load. The Elastic Modulus (EM) was determined in accordance with the Eurocode 2 regulations.

The Sorptivity and Porosity

The S test was carried out on cubic specimen; 10 × 10 × 10 cm^3 at 28 and 90 days, such that the water does not exceed 5 mm in the specimen. The rest of the sample was previously water proofed by an epoxy resin on all sides as shown in Fig. 2.

The ability of SCC was assessed by L-box test. The slump flow test of SCC was tested according to the ASTM C1621/C1621M. For all mixtures, the J-Rin test complies with the EFNARC (.

The S can be estimated using the following Eq. (1)

$$\frac{Q}{A} = s\sqrt{t} \qquad \text{... (1)}$$

where, Q represents the quantity of adsorbed water (cm^3), A is the surface of the sample in contact with water (cm^2), t is the time in second, and s is the coefficient of S of the sample ($cm/sec^{0.5}$).

The test of the P was carried out according to ASTM C642. The equation used to calculate P is the following:

$$P(\%) = \frac{B-A}{B-C} \times 100 \qquad \text{... (2)}$$

where, A the mass of oven-dried specimen, B the mass of surface-dry specimen in air after immersion and boiling and C the mass of specimen in water after immersion.

Test Results and Discussion

Fresh Properties of SCC

SCC concretes are characterized by their behaviour when fresh, a threshold of low shear and moderate viscosity, which makes it possible to obtain a homogeneous spread under the effect of its own weight, even without blocking, and without the use of vibration. After 6 minutes of mixing, the spreading and the flow time necessary to reach a spread of 500 mm (T_{500}) are determined. Spread results, J-Ring, T_{500}, V-funnel time Tv and H_2/H_1 are shown in Figs 3 & 4. It can be seen that all of the SCC studied reached the target spread of 660 ± 50 mm using the same type and dosage of super plasticizer. For each formulation of SCC, the dosage of SP is adjusted to get the target spread. SCC containing 15% of RP has a spread closer to that of the SCC_0. However, SCC formulated with 30% and 45% of RP show lower spread. Asphalt attached to RP is well known for its high water absorption. All mixtures in the test have acceptable values as per EFNARC. T_{500} time increases for concrete containing RA because it increases the viscosity due to its high porousity.[20]

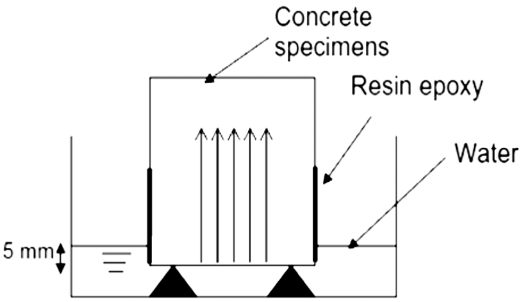

Fig. 2 — Schematic of water absorption test

The SCC exhibits good passage capacity if the difference between the spread and the J-Ring is less than 50 mm. The results illustrated in Fig. 5, show that the studied concretes meet this condition (i.e., spreading- J-Ring < 50 mm). The use of RA in SCC increases the demand for mixing water due to its high WA in pores resulting in decreased workability.[21,22] The values of the T_{500} times are higher for the

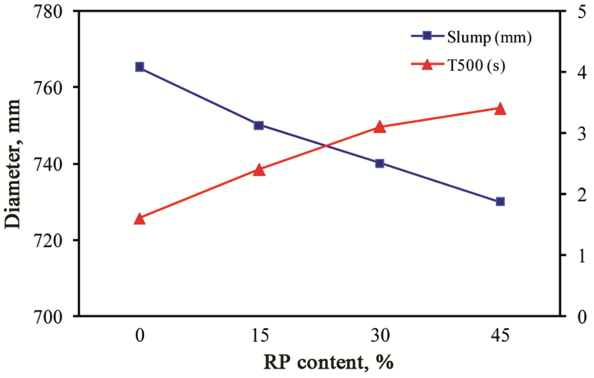

Fig. 3 — Evolution of the flow time T_{500} according to the dosage of RP

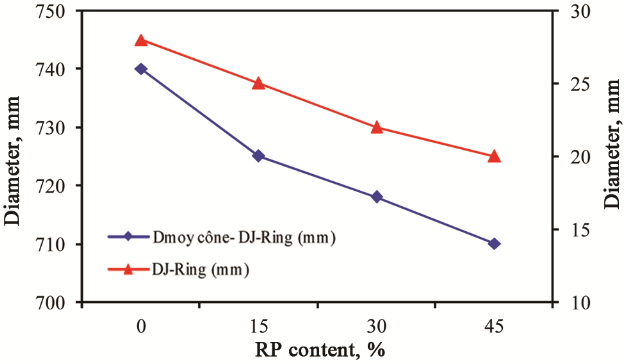

Fig. 4 — Evolution slump flow depending the dosage of RP

mixtures of SCC with a higher RA content indicating a lower plastic viscosity.

The results presented in Fig. 5 show that the flow times of the SCC_0, SCC_{15}, SCC_{30} and SCC_{45} concretes are respectively equal to 4, 7, 11 and 13 seconds. This suggests that all the formulations meet the recommendations of EFNRAC ($T_v \leq 12$ seconds) except for the SCC_{45} mixture. It is evident that the properties of the RP differ from those of NA due to the asphalt attached to the RP surface. Additionally, the hydration process can affect the cement paste in both fresh and hardened states.[23]

Hardened Properties of SCC

Flexural Strength

According to Fig. 6 the SCC_0 has developed the highest S_f compared to SCC containing RP. At 90 days the addition of 45% RP resulted in a reductionin Sc of 26% (from 3.25 to 2.4 MPa). Furthermore, at a 30% substitution rate, the reduction is limited to between 20% and 23%. The SCC containing RP develops strength regardless of the substitution rate, ranging from 15% to 45%, but it remains lower than that of the SCC_0.

There is also a good distribution of coarse aggregates around the cylinder, but it is noted that the break occurs at the level of the old interface paste and aggregate. Additionally, the S_f increases with age regardless of the addition rate. According to other research[12,24], the S_f result does not exceed 2.5 MPa at 28 days.

Compressive Strength

From the obtained results, it is evident from Fig. 7 that the use of RP instead of NA reduces the Sc in all concretes mixtures. The reduction in Sc is proportional to the replacement content of the RP. The use of 15% RP gives a similar strength to SCC_0; however, substitution level higher than 15% showed lower strength.

At later ages (90 days), the SCC_0 have a better Sc; it is of the order of 44.4 MPa, whereas the incorporating 45% results in a considerable reduction in Sc; it is of the order of 38.9 MPa. Additionally, this reduction increases with the rate of RP replacement. The weak bond between the asphalt-mortar and the quality of aggregate in RP can explain this reduction in Sc, which is consistent with the findings of other researchers.[25–27]

Therefore, it can be concluded that the use of up to 30% of RP does not negatively affect the mechanical properties of SCC. Hence, the asphalt content in RP did not significantly impact the Sc of the SCC. The negative effect of the asphalt content is partially mitigated by the increase in strength and density as well as the good bond between NA and old RP.

However, other researchers have studied the effect of asphalt mixes with construction and demolition wastes, indicating that mixing the right amount of RP and NA can lead to superior performance.[28]

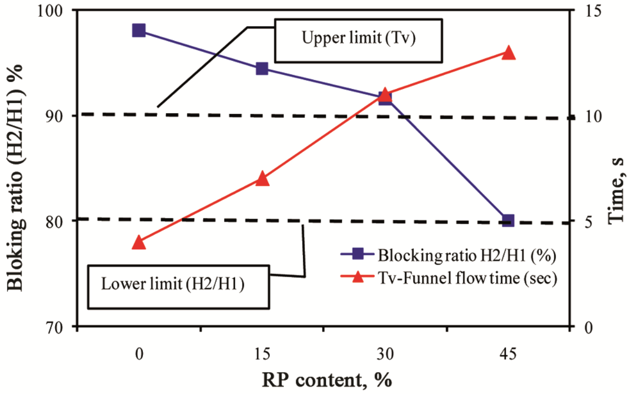

Fig. 5 — Variation of time TV-Funnel and ration H_2/H_1 depending the percentage of RP

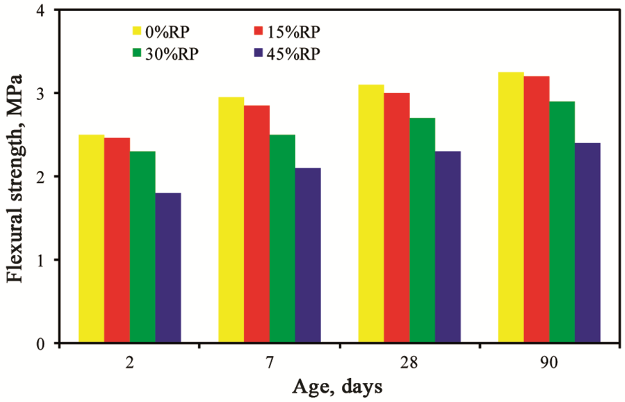

Fig. 6 — Variation of S_f depending the age for different SCC

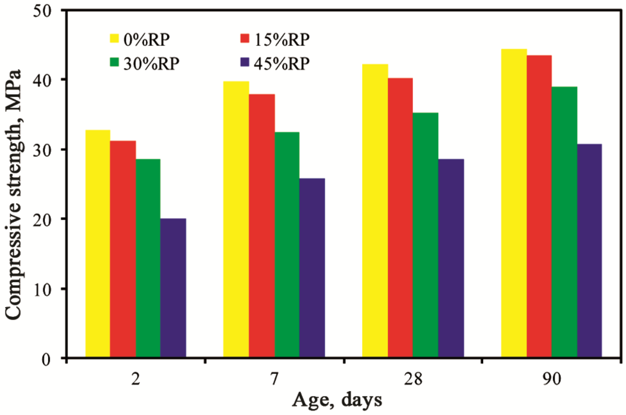

Fig. 7 — Variation of Sc depending the age for different SCC

Boukhekakl *et al.* have found that the optimal proportion used of ceramic powder or glass powder is around 5% and can be increased to 15% or 25% to obtain self-compacting mortar with better properties at hot climate.[29]

Elastic Modulus of SCC

Several researchers when comparing the SCC and OC have found no significant difference in the EM. There is no general rule to distinguish the EM of SCC from that of vibrated concrete, with equivalent mechanical resistance; both types of concrete do not seem to present any significant difference in this instantaneous mechanical property.[30]

The results obtained of EM are shown in Fig. 8. The decrease in EM of SCC with RP is influenced much more by the amount of RP used. The replacement of NA by 45% of RP causes a significant loss of about 31% in EM. For example, at 90 days, the increase in EM of SCC reached 3%, 13%, and 31% when NA was replaced by RP of 15%, 30% and 45%, respectively, compared to SCC_0. This reduction in EM was found by Saadi *et al*.[24] Contrary to what was initially thought, the quantity of bitumen attached to RP does not increase the EM of the new concrete up to 90 days of age. This is justified by the poor liaison between the new cement containing in the SCC and bitumen attached in old RP. These results were also discovered by Fiol *et al*.[31]

Sorptivity Coefficient of SCC

The S test is utilised to quantify the rate of WA by capillary suction of unsaturated samples, immersed in water without hydraulic pressure. When the capillary absorption is higher the material is more likely to be rapidly penetrated by the liquid in contact. The S values presented in the form of a histogram for a period of 28 and 90 days, are shown in Fig. 9. An increase in water permeability is observed with increasing RP content in SCC. For example, at 90 days the increase of S of SCC reached 36, 63 and 98% when NA were replaced by coarse RP of 15%, 30% and 45%, respectively, compared to reference SCC_0.

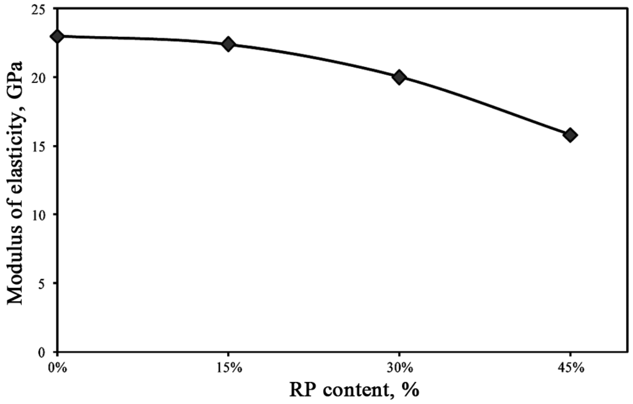

Fig. 8 — Variation of EM depending the dosage of RP

Olorunsogo & Padayachee have founded a 29% increase in WA of the concrete with 100% of RA compared to NA.[32] Additionally, some researchers[33–35], found an increase in water permeability with increasing RA content in SCC. The attached mortar is more porous than NA, resulting in greater WA of RA.[36]

Porosity of SCC

The P is defined as the ability of the sample to resist penetration by external liquid. Several factors can affect the porosity of concrete, such as quick mixing leading to increased porosity, higher water-to-cement (w/c) ratio and the use of mineral additions.[37–39]

The results of the P tests conducted on the cubes of SCC based on RA are shown in Fig. 10.

It can be observed from Fig. 10 that the P of SCC increases with RP content. The P of SCC mixture is attributed to the porosity of RP, as RP particles are

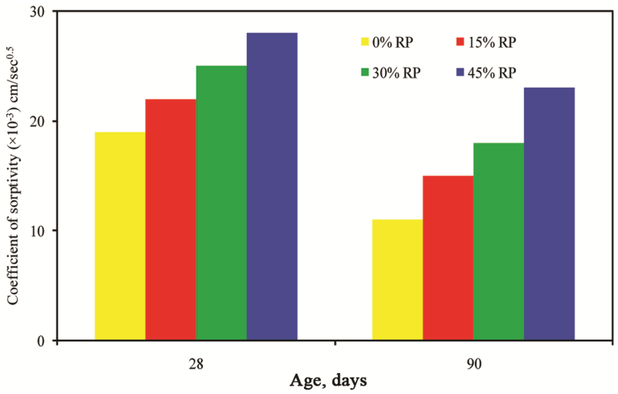

Fig. 9 — Sorptivity of SCC as a function of the age for different percentage of RP

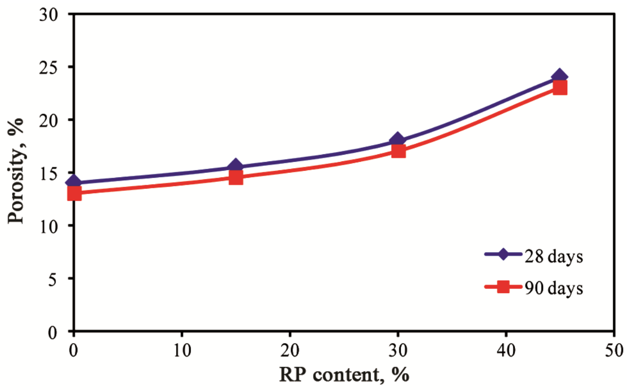

Fig. 10 — Total porosity at 28 and 90 days depending RP content

lighter and absorb more water than NA. Consequently, adding higher quantities of RP considerably increases the values of P in SCC. Based on the obtained results and the above-mentioned analysis, it seems that the SCC with 30% of RP yields better results. Therefore, a lower dosage of RP is recommended to achieve lower P. These findings are consistent with those of other researchers, who have observed an increase in porosity in concrete when fine RA is used compared to NA.[40,41]

Relationships between Hardened Properties

Correlation between Compressive Strength and Flexural Strength

The S_f increases with the increase of the Sc for all SCC samples. The relationship between the S_f and Sc is given in Fig. 11 and can be expressed as follow:

$$S_f = a(S_c)^b \quad \text{... (3)}$$

where, S_f is the flexural strength and S_C is the compressive strength, a and b are coefficients specific to the SCC specimens.

Correlation between Compressive Strength and Sorptivity Coefficients

The correlation between the S and the S_C at 28 and 90 days is showed in Fig. 12. The S coefficient reduces with the increase of Sc. These observations are in conformity with other findings.[42,43]

For all SCC samples, linear correlation between S and Sc at 90 days hardening can be adopted. According to Siad *et al.*, there reduces of strength is greater for SCC at 90 days.[44] Based on the results found, the relationships between Sc and S for SCC is given as follows: (Eqs. 4 and 5).

$$\mathrm{S} = -0.033\mathrm{S}_\mathrm{c}^2 + 1.709\mathrm{S}_\mathrm{c} + 6.046$$
$$\mathrm{R}^2 = 0{,}985(28\ \text{days}) \quad \text{... (4)}$$

$$\mathrm{S} = -0.41\mathrm{S}_\mathrm{c}^2 + 2.320\mathrm{S}_\mathrm{c} - 9.326\mathrm{R}^2 = 0.945(90\ \text{days}) \quad \text{... (5)}$$

Correlation Between Compressive Strength and Porosity

According to Assié the first parameters that should be represented as a function of Sc is P.[30] This is directly related to the Sc of specimen. The obtained results show that there is a linear relationship between Sc and P. The correlation coefficients are $R^2 = 0.982$, $R^2 = 0.992$ for 28 and 90 days, respectively. The correlation equations are written as follows:

$$\mathrm{P} = -0.719\mathrm{S}_\mathrm{c} + 44.16\ \ \mathrm{R}^2 = 0.982(28\ \text{days}) \quad \text{... (6)}$$

$$\mathrm{P} = -0.705\mathrm{S}_\mathrm{c} + 44.67\ \ \mathrm{R}^2 = 0.992\ (90\ \text{days}) \quad \text{... (7)}$$

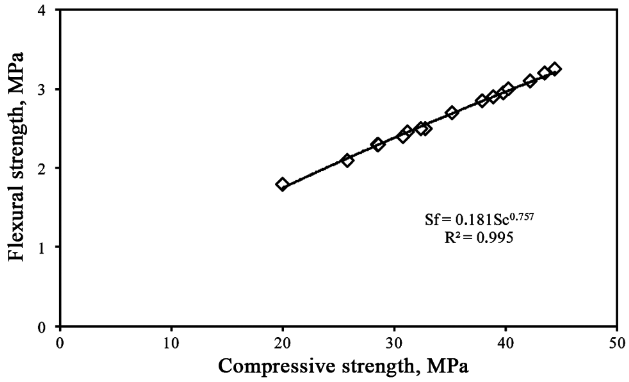

Fig. 11 — Correlation between Sf and Sc for different types of SCC w

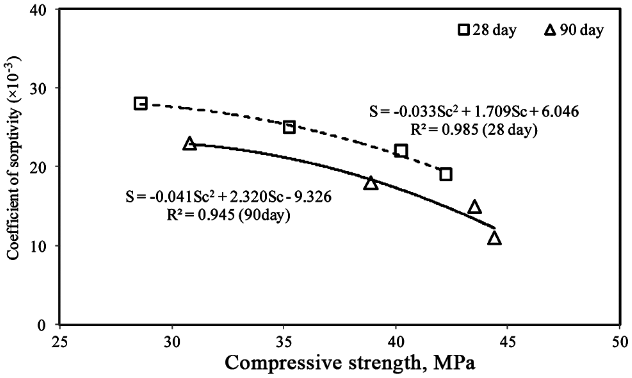

Fig. 12 — Correlation between sorptivity coefficient and Sc at 28 and 90 days

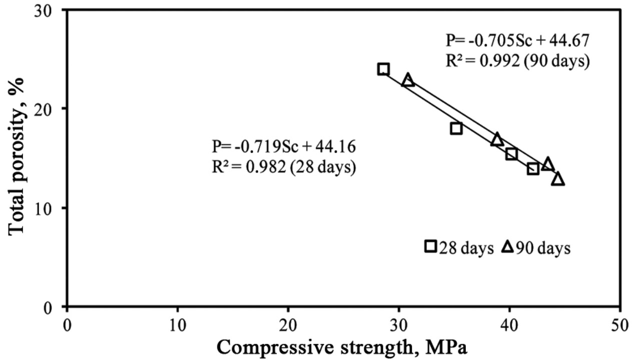

Fig. 13 — Correlation between total porosity and Sc at 28 and 90 day

The variation of P dependence on Sc at the 28 and 90 days is showed in Fig. 13, where P decreases when Sc increases. The P of concrete containing mineral additions decreases. On the other hand, the mineral addition improves Sc at a long term.[45]

Conclusions

This investigation highlights both the advantages and limitations of incorporating recycled pavement into self-compacting concrete. The use of RP in SCC mixtures has acceptable values according to regulations. Partially replacing natural aggregates with RP in SCC does not significantly affect the parameters. However, when the quantity of substitution is large the decline in some properties becomes significant.

The negative effect of the asphalt content is partially mitigated by the increase in strength and density as well as the good bond between NA and old RP. Formulating SCC with low content of RP yielded beneficial mechanical, economic, and environmental results. Consequently, it is recommended to use RP with well-determined quantities for manufacturing better SCC, which allows the recovery, recycling and valorization of large quantities of RP.

Conflict of Interest

The authors declare that they have no conflict of interest.

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