Effects of gravel type on the physico-mechanical characteristics of self-compacting concretes reinforced with steel fiber

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Abstract

It has become vital to look for alternatives to the non-renewable natural resources utilized in the building industry due to the vast and quick expansion in that sector in order to safeguard such resources from waste. Recycling varied concrete debris from demolished concrete buildings to substitute natural gravel in the production of various concrete mix types is one way to do this. In this study, the physico-mechanical characteristics of steel fiber-reinforced self-compacting concrete made of quartz gravel were examined. The percentages of recycled gravel used to replace the quartz gravel were 25, 50, and 75%, respectively. According to the findings, up to 75% of the quartz gravel may be replaced with recycled gravel. The correlation between the concrete's ultrasonic speed and mechanical strength was strong and promising.

Keywords: self-compacting concrete, steel fiber, physico-mechanical properties, open porosity, quartz gravel, recycled gravel, correlation.

1. Introduction

Since its discovery, concrete has been used by everyone and for all types of construction. This has led to a rise in demand for non-renewable natural materials used in concrete [1, 2], especially inert materials like coarse and fine natural aggregates, to supply the construction and public works industries in all their forms. The advantage of making concrete is that it does not require a lot of resources and is easy to handle before hardening. It has been ranked as the second-most consumed substance in the world after water [3]. Experts and statisticians say that by 2050, the amount of concrete needed each year will rise to approximately 7.5 million cubic meters [4, 5]. About 70% to 80% of the volume of concrete is made up of sand and gravel [6], so it's important to think about what other materials could be used instead. One of the results has been the use of recycled materials, the most important of which is that resulting from old concrete waste (whether from natural disasters or from the demolition of old structures). The use of recycled concrete materials in construction is now a major priority in all countries, and every year new research is carried out in this area. The most important gains of using recycled concrete materials are, first, the protection of nature against construction waste, which often ends up in landfills, so the use of recycled concrete materials reduces landfills and has positive effects on the environment [7– 10]. This allows saving the energy used in extracting natural gravel and transporting it from quarries [11, 12]. Secondly, savings on building expenses by employing building waste in general as a replacement for natural resources may approach 60% [13]. At the same time, reducing carbon dioxide emissions [CO_2] from gravel extraction [12, 14–19].

Each stage has its own construction requirements, which has encouraged manufacturers to keep pace by looking for ways to improve the quality of concrete to expand its use. In 1988, it saw the beginning of self-compacting concrete (SCC) and the intensification of studies on it. Compared to ordinary concrete, self-compacting concrete is characterized by its high fluidity and its ability to reach narrow and highly confined spaces without vibration from anything but its own weight. Using recycled gravel in self-compacting concrete can improve some of these properties and also reduce its relatively high costs if there are plasticizers in its components [20]. According to research by Bani et al. [21], the rate of replacement of natural gravel by recycled gravel varies depending on the uses. The rate of replacement can reach 80%. Omrane et al. [22] found that the mechanical properties of SCC were better when 50% of the sand and natural gravel were replaced with recycled concrete materials.

The majority of research have shown that adding fibers at random to a concrete mold considerably enhances numerous technical features. High-performance concrete becomes more ductile with the inclusion of fibers [23, 24]. The use of fibers in the SCC is a possible solution to improving the properties of concrete in its hardened state. Researchers [25, 26] state that adding fibers according to their type has benefits, such as increased fracture energy, prevention of sudden failures, improved tensile strength, and reducing the risk of SCC cracking. According to Awang's research [27], cellular concrete's mechanical qualities and durability are enhanced when any kind of synthetic or natural fiber is used. There are a number of techniques to evaluate the safety and quality of completed or currently under construction concrete structures, even in laboratories. One of these is the ultrasound pulse velocity measurement, which is regarded as one of the most significant non-destructive testing techniques [28–39].

All previous studies have shown that the compressive strength of concrete and the speed of its ultrasonic pulse do not have a special or fixed relationship. It depends on many things, like the size and type of the sand and gravel, the quality and the type of the cement, the age of the concrete, and its curing method [40–47]. In order to determine what would happen if recycled fine and coarse aggregates were used in place of natural aggregates, researchers looked at the link between compressive strength development and ultrasonic pulse velocity [48–50]. Concrete with steel fibers was examined by Al-Ridha et al. [51]. The findings showed a correlation between an increase in the fraction of mineral fibers and an increase in the impulse velocity. Many researchers [52–55] have studied various empirical correlation models to discuss the connection between UPV and the strength of concrete at any age. Finding a link between ultrasonic pulse velocity (UPV) and compressive strength (Cs) may be used to evaluate concrete quality characteristics like Cs. Both exponential and linear correlations exist. Exponential connections often come in the form of ($C_S = \beta_1 * \text{EXP } \beta_2 * V_{ul}$).

In this study, the effects of using recycled gravel in place of quartz gravel on the characteristics of self-compacting concrete (SCC) reinforced with steel fibers are examined. This substitution was made in varying amounts of 25, 50, and 75%. Before discussing the physics and mechanics properties of the hardened state, the properties of the fresh state have been studied. In addition, the present study is different from the others available because of the correlation between the different physico-mechanical properties, such as concrete's density, ultrasonic pulse velocity, and compressive strength, which gives benefit to this study.

2. Experimental program

2.1. Materials

Table 1 lists the physical characteristics, mineralogical makeup, and chemical composition of cement class 42.5 MPa (CEM II/B) used. Bogue's method was used to compute the mineral compositions [56]. The replacement was at rates of 25%, 50%, and 75% of the natural quartz gravel in the two granular grades [8/16 and 3/8] with recycled gravel. In Table 2, their physical characteristics are shown. All SCC combinations include natural alluvial sand [0/5], whose characteristics are listed in Table 2. Table 3 shows the mechannical and physical properties of the steel fibers used in this research. Laboratory water was used to create all mixtures of SCC. "MEDAPLAST SP 40" is a 40% solids-by-volume ether polycarboxylate-based superplasticizer (SP) used in this research with a density of 1.20 ± 0.01 a pH of 8.2, and a chlorine ion content of 1 g/L. For the formulation of all SCC in this study, the ratio (W/C) is 0.42. For all SCC combinations, we set the superplasticizer (SP) content at 2.45% of the cement weight. Table 4 presents the different SCCs formulated along with their abbreviations.

2.2. Tests used in the fresh and hardened states

To confirm that the concrete is self-compacting in this study, the first stage is to conduct rheological testing in accordance with EFNARC 2005's guidelines [57], and the second step is to conduct physical and mechanical tests on the hardened concrete. All the tests performed on all the SCCs are shown in Figure 2.

Table 1. Physical and chemical properties and mineralogical composition of cement

Physical properties (kg/m^3)			**Mineralogical composition (%)**			
Specific density	3050		C_3S	C_2S	C_3A	C_4AF
Apparent density	1100		55.41	13.65	2.25	14.83
Fineness (cm^2/g)	4180					

Chemical composition (%)

SiO_2	CaO	Fe_2O_3	Al_2O_3	MgO	SO_3	Na_2O	K_2O	LOI
17.49	62.78	3.02	4.51	2.15	2.38	0.05	0.64	8.10

Table 2. Physical-mechanical properties of sand and two types of gravel

Physical property	**Sand**	**Gravel**			
	Alluvial	**Quartz**		**Recycled**	
	(0/5)	**$(3/8)_Q$**	**$(8/16)_Q$**	**$(3/8)_R$**	**$(8/16)_R$**
Apparent volume mass (g/cm^3)	1.55	1.31	1.32	1.21	1.23
Absolute density mass (g/cm^3)	2.64	2.70	2.69	2.56	2.58
Degree of absorption (%)	1.35	2.2	2.15	6.9	6.2

Fineness modulus	2.29	–	–	–	–
Sand equivalent (%)	89	–	–	–	–
Porosity e (%)	–	–	0.54	–	14.1
Los Angeles Coefficient (%)	–	22.8	22.7	30.5	26.4

Table 3. Characteristics of the steel fibers used

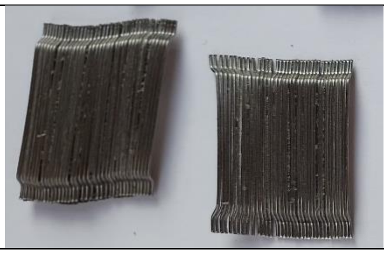
Characteristics			**Figure 1.** Steel fiber used
Density		7840 (Kg /m^3)	
Tensile strength	>	1100 MPa	
Geometry of steel fiber used		L_f = 30 mm	
		D_f = 0,55 mm	
Aspect ratio (L_f/D_f)		55	

Table 4. The different BAP formulations with their abbreviations (kg/m^3)

Mixture abbreviation	**Cement**	**Water**	**Sand**	**Gravel**				**Fiber**	**S_P (%)**	**Ratio**	
				Quartz		**Recycled**					
			0/5	**$(3/8)_Q$**	**$(8/16)_Q$**	**$(3/8)_R$**	**$(8/16)_R$**			**W/C**	**G/S**
$SCC_{Q\text{-}0R}$	450	189	888,86	270,58	541,16	–	–	–	2.45	0.42	0.91
$SCC_{fQ\text{-}0R}$	450	189	849.66	270,58	541,16	–	–	39.2	2.45	0.42	0.96
$SCC_{fQ\text{-}25R}$	450	189	849.66	202.9	405.88	67.64	135.3	39.2	2.45	0.42	0.96
$SCC_{fQ\text{-}50R}$	450	189	849.66	135.3	270.58	135.3	270.58	39.2	2.45	0.42	0.96
$SCC_{fQ\text{-}75R}$	450	189	849.66	67.64	135.3	202.9	405.88	39.2	2.45	0.42	0.96

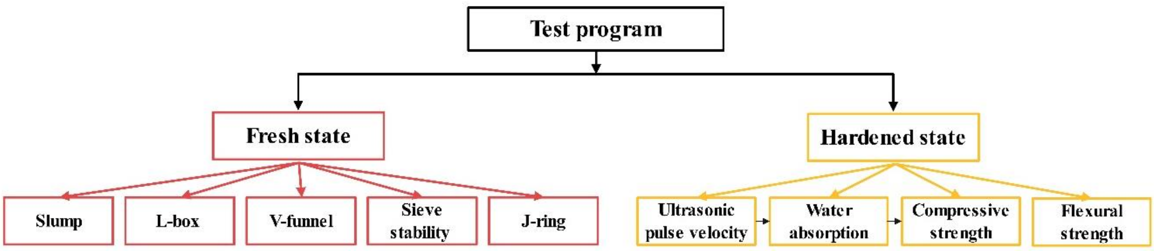


Figure 2. Test programs in fresh and hardened states

The identical cubic specimens (10x10x10) cm^3 were subjected to three tests in the hardened state at 28, 56, 90, and 120 days in order to examine the connection between the outcomes. All of these experiments were conducted for two different cure regimens: 28 days in water and in the open air in the laboratory.

- Examination of ultrasonic pulse velocity (UPV) [58], It is a test in which concrete samples are used to assess ultrasonic propagation velocity, and its benefit is that it is a non-destructive test. The apparatus that was used to measure ultrasonic pulse velocity is shown in Figure 3.

Figure 3. Measurement of the propagation speed of ultrasonic waves (UPV)

- The capillary absorption test for water includes submerging concrete samples in a container of water at a height of no more than half a centimeter in order to quantify the amount of water that is absorbed. Water is only absorbed in one direction, from bottom to top, thanks to sticky plastic tape covering the sample's four edges to stop water leaking from those four sides. The sequential sample weights are used to determine how much water was absorbed. Before being weighed, the residual water film on the sample's bottom was wiped using a paper towel. The water absorption experiment is shown in Figure 4. The void volume (V_{Vo}) divided by the total volume constitutes the open porosity (ε). (V_{Tot}). How to compute it is given in equation (1):

$$\varepsilon(\%)=(V_{Vo}/V_{Tot}).100\%=((\Delta m/A)/\rho_{wat}.H_{fron}).100\% \quad (1)$$

Where, ε : Open porosity (%); Δm/A : Amount of water absorbed per unit area (kg $/m^2.h^{1/2}$);
ρ_{wat} : Water density (ρ_{water} = $1 g/cm^3 = 10^3 kg/m^3$); H_{fron}: The frontal capillary imbibition height ($H = 4\ cm.h^{-1/2} = 0.04\ m.h^{-1/2}$).

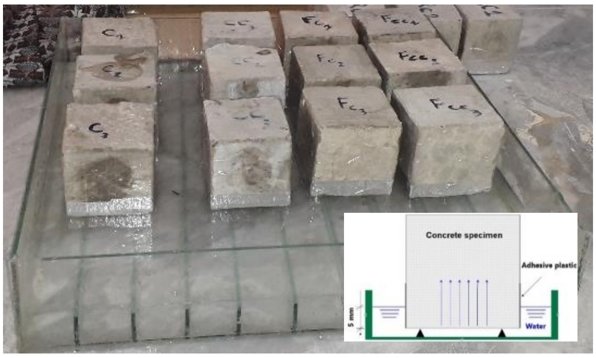


Figure 4. Water absorption test

- Compressive strength: BS EN Standard 12390-3 [59]. A hydraulic press with a 3000 kN capacity was used to evaluate the compressive strength on the identical cubic samples that were utilized in the previous two experiments. Figure 5 shows the device used to measure compressive strength.

Figure 5. Device used to measure compressive strength

- Test for three-point bending strength on rectangular specimens in accordance with BS EN 12390-5 [60] (7 x 7 x 28 cm^3). Figure 6 shows the device used to measure three-point bending strength.

Figure 6. Device used to measure three-point bending strength.

3. Results and discussion

3.1. Fresh state results

Table 5 presents the findings for all kinds of fresh concrete. All results satisfied all SCC standards, which was in line with the advice given by EFNARC [57]. Additionally, based on our observations of the concrete, we found no segregation or bleeding for all SCC mixes.

3.2. Hardened state results

3.2.1. Density of self-compacting concrete

According to the results presented in Figure 7, self-compacting concrete (SCC) made from quartz gravel and without steel fibers (SCC_{fQ-0R}) has a lower density than the same kind of SCC made with steel fibers. Given that the steel fibers have a larger density than the other materials employed in the SCC, this outcome makes perfect sense. The density of steel fiber reinforced self-compacting concrete decreased as the replacement rate of quartz gravel with recycled gravel increased. At 25%, 50%, and 75% substitution of the quartz gravel with recycled gravel, the density of SCC_{fQ-0R} reduces by 0.51%, 0.95%, and 1.4%, respectively, with a step of 0.45%. These outcomes are the consequence of recycled gravel having a lower density than quartz gravel.

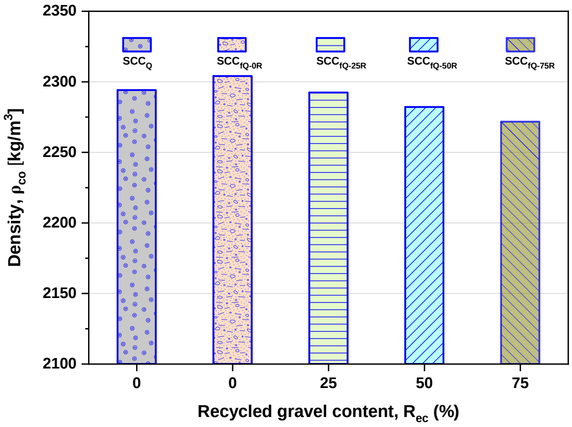


Figure 7. Effect of recycled gravel and steel fibers on density

Table 5. The properties of the different types of SCC in the fresh state

Concrete type	Test								
	Slump		L-Box			V-funnel	Sieve stability	J-Ring	
	T_{500} (S)	D (mm)	T_{200} (S)	T_{400} (S)	H_2/H_1 (%)	t_v (S)	Π (%)	D (mm)	DH (mm)
	≤ 5	660 – 750	≤ 1.5	≤ 3.5	80% à 85	5 à 12	0% à 15	650 à 750	≤ 10
SCC $_{Q-0R}$	1.93	736	1.35	2.60	84.05	7.20	6.65	717.5	8.3
SCC $_{fQ-0R}$	1.95	728	1.15	2.00	83.70	7.10	7.00	712.5	8.5
SCC $_{fQ-25R}$	2.29	731	1.10	1.85	84.66	7.00	7.30	710	8.4
SCC $_{fQ-50R}$	3.02	736	1.05	1.80	86.00	6.75	7.55	715	8.2
SCC $_{fQ-75R}$	3.00	742	1.00	1.80	87.35	6.55	7.75	722.5	7.9

3.2.2. Open porosity

Figure 8 illustrates the increase in open porosity of SCC_{fQ-0R} steel fiber self-compacting concrete when additional recycled gravel is used instead of quartz gravel. Due to the fact that curing in water promotes hydration, which clogs existing capillary holes and strengthens connections between granule cells, all SCCs benefit from a reduction in their open porosity after 28 days of curing in water. For instance, we can plainly observe that in the case of SCC_{fQ-75R} (water curing), the curing process decreased the open porosity after 28 days by 16.22% and 18.18% at 120 days, respectively, compared to SCC_{fQ-75R} (air curing). According to [61], this result is plausible.

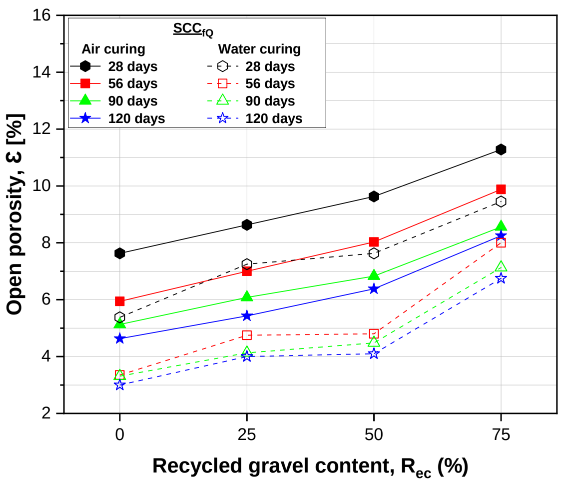


Figure 8. Effects of recycled gravel on the open porosity of SCC_{fQ} in two curing regimes

3.2.3. Compressive strength

At all ages, the compressive strength of all self-compacting concrete mixtures based on steel fibers shows a small improvement (see Figure 9). Additionally, Figure 9 demonstrates how the replacement rate of quartz gravels by recycled gravels is a decreasing function of the compressive strength (Cs) of $SCC_{fQ\text{-}0R}$ at various ages; this is in agreement with the results obtained in [22]. We can see that water curing has a positive impact on enhancing compressive strength by comparing the results of concrete cured in water with concrete cured in air. Curing specimens in water for 28 days results in compressive strengths of self-compacting concretes approximately 9–24% higher at all ages compared to SCC in the air. SCC_f with 75% recycled gravel ($SCC_{fQ\text{-}75R}$) at 120 days gives results close to those of SCC based on quartz gravel alone at 28 days. Therefore, this replacement has the advantage of safeguarding natural sources of debris and preventing environmental damage caused by concrete blocks left over from the demolition of old structures or after earthquakes.

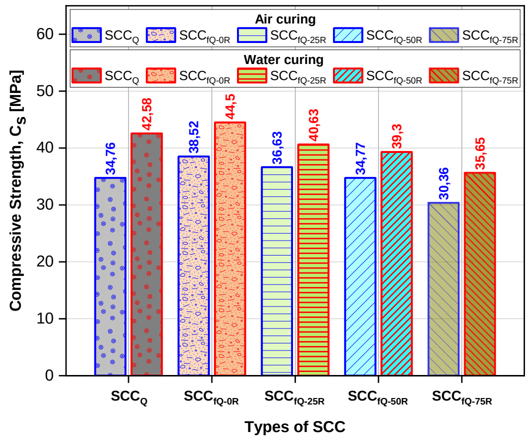


Figure 9. Results of compressive strength tests

3.2.4. Flexural tensile strength

Figure 10 shows that regardless of whether a combination is cured in water or in the open air, its behavior with regard to flexural strength is roughly similar to that of compressive strength. Self-compacting concrete positively benefits from the use of steel fibers. Tensile strength (Ts) has upper values of 5.88; all results range between 5.88 and 10.2. Concrete preserved in water always produces better results than concrete exposed to the air. For instance, the substitution of 25% of quartz gravel with recycled gravel ($SCC_{fQ\text{-}25R}$) at 120 days gives the best result of Ts = 10.2 MPa (water curing) and Ts = 8.69 MPa (air curing).

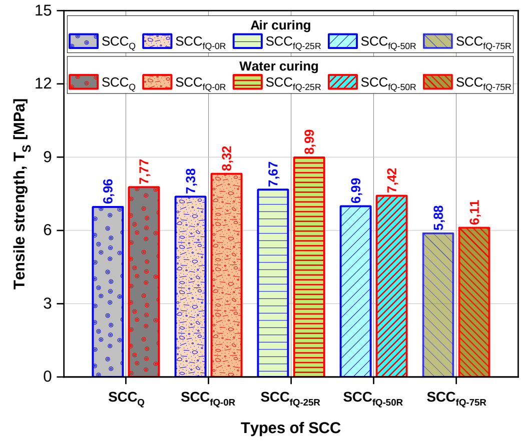


Figure 10. Results of tensile strength tests

3.2.5. Ultrasonic pulse velocity (UPV)

The graphical representation in Figure 11 shows that the ultrasound velocity V of all types of concrete evolves in the same way as that of compression. The ultrasound velocity decreased as a function of the increase in recycled gravel. Additionally, the nature, adhesion, and size of the types of gravel and the material density have an effect on the decrease and increase of the V (m/s) that passes through the concrete. The quality of all SCC mixtures is good-quality concrete, according to IS 13311-1 (1992) [62]. Ultrasound velocities have upper values of 4248.69; all velocities range between 4248.69 and 4437.43.

For instance, the substitution of 75% of quartz gravel by recycled gravel $SCC_{fQ\text{-}75R}$ at 120 days gives a better result in terms of ultrasonic velocity V = 4350.63 m/s than that of concrete $SCC_{fQ\text{-}0R}$ at 28 days with V = 4301.08 m/s (at air hardening), and at the water hardening regime, the results of the same type of concrete $SCC_{fQ\text{-}75R}$ are V = 4392.58 m/s.

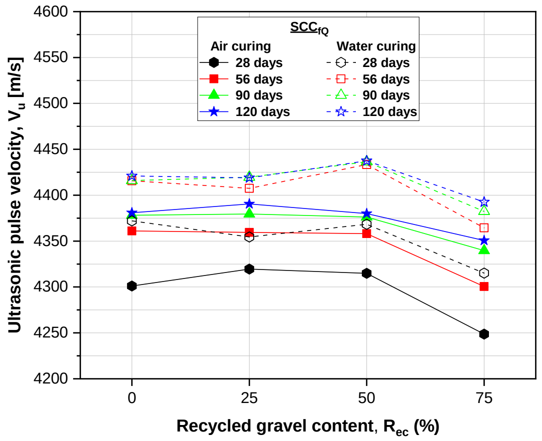


Figure 11. Results of the ultrasonic pulse velocity (UPV)

4. Correlation between the SCC's compressive strength and its ultrasonic pulse velocity

The results obtained for all of the SCC studied at different ages allowed us to establish an exponential correlation between the (C_S) compressive strength of each type of SCC ($SCC_{Q\text{-}0R}$, $SCC_{fQ\text{-}0R}$, $SCC_{fQ\text{-}25R}$, $SCC_{fQ\text{-}50R}$, and $SCC_{fQ\text{-}75R}$) and its associated (V_u) ultrasonic pulse velocity and their (ρ_{co}) density as in [61].

$$C_S\ (MPa) = \beta_1 \times EXP\ (\beta_2) \quad (2)$$

$$\beta_1 = 0.84 \times \rho_{moy}\ (Kg/m^3) \times 10^{-6} \text{ and}$$
$$\beta_2 = V_u(m/s) \times \rho_{co}\ (Kg/m^3) \times 10^{-6} \quad (3)$$

Where, β_1 & β_2 are the exponential equation's regression coefficients.

$$C_S\ (MPa) = 0.84 \times \rho_{moy}\ (Kg/m^3) \times 10^{-6} \times EXP\ (V_u(m/s) \times \rho_{co}\ (Kg/m^3) \times 10^{-6}) \quad (4)$$

$$C_S\ (MPa) = 1922.67 \times 10^{-6} \times EXP\ (V_u(m/s) \times \rho_{co}\ (Kg/m^3) \times 10^{-6}) \quad (5)$$

Regression coefficient (R^2= 0.973)

Figure 12 shows this empirical correlation graphically. We see that advanced correlation joins the correlation found in [63]. The relative error (%) is the difference between the measured compressive strength ($Cs_{(M)}$) and the estimated compressive strength ($Cs_{(E)}$) (calculated by formula (5)). At all ages, the results are less than 5%, so we can estimate the compressive strength of SCC concrete at different ages without crushing it.

$$\left|\frac{\Delta Cs_j}{Cs_{j\,(E)}}\right| = \left|\frac{Cs_{j\,(E)} - Cs_{j\,(M)}}{Cs_{j\,(E)}}\right| \quad (\%)$$

(6)

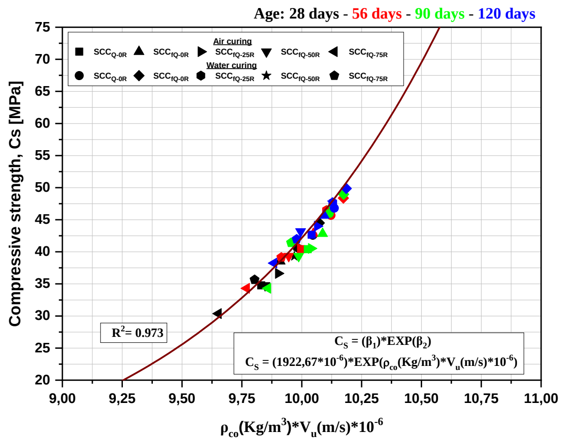


Figure 12. Correlation between C_S, V_u, and ρ_{co}.

5. Conclusion

Following are the key experimental findings from this investigation about the mechanical and physical characteristics of the hardened state of self-compacting concrete reinforced with steel fibers based on quartz gravel (SCC_{fQ}) and those recycled (by the replacement of 25%, 50%, and 75% of the quartz gravel):

- As the amount of recycled gravel goes up, the density of self-compacting concrete made from quartz gravel and steel fibers goes down.
- The open porosity increases as the proportion of recycled gravel in the $SCC_{fQ\text{-}0R}$ increases, regardless of the age of the concrete at the time of measurement.
- Water curing has a positive effect on all self- compacting fiber reinforced concrete (SCC_f) by decreasing their open porosity and increasing their ultrasonic velocity (UPV), compressive strength, and tensile strength in flexion.
- When 25% recycled gravel is used instead of quartz gravel, SCCFQ concrete has better flexural tensile strength.
- The substitution of 75% of quartz gravel with recycled gravel for SCC_{fQ} gives good results at 120 days on the compressive strength and the speed of ultrasound compared to that of $SCC_{fQ\text{-}0R}$ concrete at 28 days. This encourages the use of recycled gravel in certain areas.
- The physical-mechanical parameters (compressive strength, ultrasonic velocity, and various concrete densities) were correlated for SCCf in the presence of quartz gravel and recycled gravel, and the results were excellent and acceptable.

6. Field of use for recycled gravel

The use of recycled gravel resulting from the demolition of all kinds of concrete leads to the provision of gravel for various public works' needs, including preserving the environment and the fight against the excessive exploitation of natural sources. The percentage of recycled gravel in concrete varies according to its use and purpose.

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