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# Valorization of glass powder as filler in self-compacting concrete

**Keywords:** compressive strength, limestone filler, mechanical properties, recycled glass powder, self-compacting concrete, workability

## Introduction

Self-compacting concretes appeared in 1980, and continue to be the subject of several research projects aimed at formulating more environmentally friendly self-compacting concretes with improved technical characteristics. However, this progress can only be realized with the development of new formulation approaches, the use of new additions, and the recovery of waste. Also, self-compacting concrete (SCC) is currently an appealing product because it can significantly reduce labor and time requirements (Ruslan et al., 2024).

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In Algeria, household waste annual production is around 13.5 million tons per year, and the recovery of glass is estimated at 41,724 tons per year, or about 1.04% of the annual production. This rate remains relatively low compared to other sectors. Unfortunately, glass is ranked last compared to other recycled materials (National Waste Agency [NWA], 2020). The limestone filler is largely used as an addition to SCC (Petersson, 2001; Jiang et al., 2024; Martinez-Echevarria et al., 2024). Research has thus shown that fillers exhibit some physical-chemical activity, which promotes the acceleration of clinker hydration and contributes to a pozzolanic reaction (Zhu & Gibbs, 2005; Diederich et al., 2013). The valorization of glass waste in the field of materials could be an interesting ecological and economical solution (Zhao et al., 2024). Glass powder (GP) has now become an effective addition to the field of building materials. Its rheological performance, strength, and durability have been proven in several types of concrete (Carlswärd et al., 2003). The introduction of GP in concrete dates back to the 1960s and the use of glass as aggregates in concrete has been investigated (Pike et al., 1960). Johnston (1974) used GP as an addition to cement for ordinary concrete. Nishikawa et al. (1995) showed that the strength of ordinary concretes would increase with the content of glass mixtures and that the simultaneous use of glass and natural pozzolan to partially replace cement was of interest in the research. The strength testing and durability of ordinary concrete using glass waste as aggregate yielded acceptable results (Polley et al., 1998). The prediction of the glass aggregate effect size on concrete swelling has been investigated by Zhang et al. (2021). The chemical composition of glass plays a significant role in its mechanical properties, including compressive strength (Karamberi & Moutsatsou, 2005). Batayneh et al. (2007) studied sand substitutions rather than cement by comparing glass to other pozzolanic materials. Mourad and Tahar (2013) invested in partial cement substitution with GP in SCC. The work of Malafalda Matos and Sousa-Coutinho (2016) consisted of collecting relevant information on the sustainability of SCS manufactured using GP addition. Arabi et al. (2019) examined the possible incorporation of both coarse recycled concrete aggregates and coarse recycled windshield glass aggregates in the composition of SCS. Singh and Siddique (2022) studied the possible utilization of glass waste in the production of SCC and showed that the rheological parameters were improved. Ahmad et al. (2023b) explore sustainable alternatives for self-compacting concrete by using waste glass powder as a cement substitute and incorporating marble waste as a filler material. The levels of powder glass replacement ranged from 0% to 20%, in 5% increments, while 10% marble waste was added to enhance SCC flowability. All waste glass powder substituted mixes met SCC's standards and exhibited improved filling and passing abilities. The study shows mechanical performance was enhanced with waste glass powder substitution due to micro--filling and pozzolanic actions. Scanning electron microscopy and Fourier transform infrared analysis provided visual and chemical evidence of the microstructural improvements from pozzolanic reactions and micro-filling effects.

The research work conducted by Ahmad et al. (2023a) has concluded that self-compacting concrete with 22.5% glass powder shows the highest increases in compressive, tensile, and flexural strengths (16.99%, 23.53%, and 17.65%, respectively) compared to other mix designs. Although there is a slight reduction in strength parameters, concretes with 30% glass powder still outperform the control design, and the same analysis confirms that the replacement of cement with glass powder addresses environmental issues related to cement production and glass waste disposal, while also enhancing concrete properties and lowering production costs by approximately 23.67%.

Indeed, formulations were prepared by substituting the filler with glass powders up to 100%, which is not the case in current literature. Fresh and hardened tests were conducted to achieve a more suitable SCC in terms of workability and compressive strength.

## Experimental procedure

### Materials

The aggregates are crushed limestone obtained from a Béjaia quarry in Algeria. The sand (S) used is of alluvial origin, with a nominal particle size of 4 mm; the gravel (G) used has two fraction sizes (4/8 and 8/16 mm). The physical properties of fine and coarse aggregates are shown in Table 1. The grading of aggregate mixtures is presented according to references issued by the NF EN 933-1 standard (Association française de normalization [Afnor], 2012). Furthermore, the cement (C) utilized is CPJ-CEMII-42.5A, originating from the local cement plant in Ain Kebira, Setif. The chemical analysis of the cement used in the study is given in Table 2. The additive used is a high-performance water-reducing superplasticizer of the new generation, known as MEDAFLOW 30, produced by GRANITEX Building Chemicals Company. It is a polycarboxylate solution with a 30% solid content, a light brown color, and a pH ranging between 6 and 6.5. The filler (F) used is the limestone UF5-type filler from the ENG El-Khroub quarry. Its chemical composition is presented in Table 2. The GP used in this study was obtained by crushing glass waste from public landfills (Figs 1 and 2). Its chemical composition is listed in Table 2.

Serikma, M., Benahmed, B., Kennouche, S., Mohd Hashim, M. H., Merabti, S. (2024). Valorization of glass powder as filler in self-compacting concrete. *Sci. Rev. Eng. Env. Sci.*, *33* (3), 261–277. DOI 10.22630/srees.9810

TABLE 1. Physical properties of various used materials

| Characteristics | Standard | Fine aggregate | Coarse aggregate | C | F | GP |
|---|---|---|---|---|---|---|
| Fineness modulus | NF EN 12620 | 2.91 | – | – | – | 3.12 |
| Absolute density [g·cm$^{-3}$] | NF EN 1097-6 | 2.63 | 2.67 | 3.11 | 2.45 | 2.55 |
| Bulk density [g·cm$^{-3}$] | NF EN 1097-6 | 1.45 | 1.41 | 1.12 | 0.85 | 0.89 |
| Sand equivalent [%] | NF EN 933-8 | 81.12 | – | – | – | 71.38 |
| Compactness [%] | NF EN 1097-6 | 58 | – | – | – | – |
| Water absorption [%] | NF EN 1097-6 | 1 | 0.03 | – | 0.00 | – |

Source: own work.

TABLE 2. Chemical compositions of cement, filler, glass powder, and aggregate

| The samples (100%) | Cement | Filler | Glass powder | Aggregate |
|---|---|---|---|---|
| Silicon dioxide ($SiO_2$) | 21.26 | 0.39 | 73.89 | – |
| Aluminum oxide ($AI_2O_3$) | 3.83 | 0.11 | 1.72 | – |
| Iron oxide ($Fe_2O_3$) | 2.91 | 0.06 | 1.24 | – |
| Calcium oxide (CaO) | 61.22 | 57.94 | 10.12 | – |
| Magnesium oxide (MgO) | 1.17 | 0.17 | 2.44 | – |
| Sodium oxide ($Na_2O$) | 2.05 | 0.07 | 9.05 | – |
| Potassium oxide ($K_2O$) | – | 0 | 0.25 | – |
| Sulfur trioxide ($SO_3$) | 1.18 | 0.05 | 0.21 | – |
| Chromium oxide ($CrO_2$) | – | – | 0.12 | – |
| Calcium carbonate ($CaCO_3$) | – | – | – | 96.18 |
| Other | – | – | – | 2.95 |
| Loss on ignition | 6.24 | 40.65 | 0.95 | – |

Source: own work.

FIGURE 1. Glass in the landfill
Source: own photo

FIGURE 2. Glass crushing
Source: own photo

A granulometric analysis (Fig. 3) was conducted to validate the computation and ensure that the analysis curve aligns with the specified range outlined in the NF EN ISO 17892-4 standard (Afron, 2018).

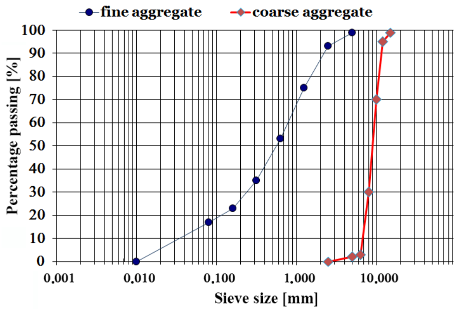


FIGURE 3. Grain size of fine and coarse aggregates distribution

Source: own work.

## Concrete mixtures

For the experimentation, eleven types of concrete mixes were made. In each mix, filler was replaced by (GP) at the rates of 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% by weight.

The preliminary mix design was carried out using a prescribed method reported by Okamura and Ouchi (2003).

The dosage of the superplasticizer, as well as the water-to-cement and filler-to-cement ratios, remained consistent for all SCC mixtures; $\frac{W}{C} + F = 0.35$; $\frac{F}{C} = 0.2$; $\frac{SP}{C+F} = 0.014$; and $\frac{F}{F+C} = 0.2$. The compositions of different mixes are given in Table 3.

TABLE 3. Self-compacting concrete mix proportions

| Mixture | Cement [kg·m$^{-3}$] | Filler [kg·m$^{-3}$] | Glass powder [kg·m$^{-3}$] | Coarse aggregate [kg·m$^{-3}$] | Fine aggregate [kg·m$^{-3}$] | Super-plasticizer [kg·m$^{-3}$] | Water [l·m$^{-3}$] |
|---|---|---|---|---|---|---|---|
| SCC0 | 400 | 100 | 0 | 783 | 779 | 7 | 175 |
| SCC1 | | 90 | 10 | | | | |
| SCC2 | | 80 | 20 | | | | |
| SCC3 | | 70 | 30 | | | | |
| SCC4 | | 60 | 40 | | | | |
| SCC5 | | 50 | 50 | | | | |
| SCC6 | | 40 | 60 | | | | |
| SCC7 | | 30 | 70 | | | | |
| SCC8 | | 20 | 80 | | | | |
| SCC9 | | 10 | 90 | | | | |
| SCC10 | | 0 | 100 | | | | |

Source: own work.

## Test method

After the mix design, the formulated concretes must satisfy several standard tests, such as the NF EN 206-9 standard (Afron, 2010b). The trial mixes were prepared and tested to assess two characteristics: workability and mechanical strength.

### Workability

Workability refers to the ease of handling fresh concrete. These characteristics can be divided into three measurable criteria through empirical tests:

– The concrete filling capacity is a criterion directly influenced by its fluidity and was evaluated using the slump flow test according to the NF EN 12350-8 standard (Afron, 2010a).
– The flow, which denotes the ability to pass through obstacles such as narrow sections of formwork or closely spaced reinforcement bars, is primarily influenced by the characteristics of the aggregates and the volume of paste, as evaluated by the L-box test according to the NF EN 12350-11 standard (Afron, 2010d).
– The resistance to segregation of SCC is attributed to its high fluidity and paste content. Ensuring the stability of fresh materials is necessary to guarantee the uniformity of mechanical characteristics in the final structure. The stability was evaluated with sieve segregation test according to the NF EN 12350-10 standard (Afron, 2010c), which allowed checking the resistance against segregation of our concretes.

### Mechanical strengths

The compressive strength was measured using cylindrical specimens for each type of SCC. It should be noted that six specimens were used for each test. Thus, a total of 66 (11 × 22 cm) concrete cylinders were prepared. The concrete was poured into the molds without the use of vibration. The specimens were then kept in their molds for 24 hours before being demolded and then fully immersed in water at a temperature of 20°C for curing periods of 7 days and 28 days, respectively. The results are presented in Table 4.

TABLE 4. Characterization experimental results

| Mixture | Slump flow test [mm] | L-box test ($H_2/H_1$) [%] | Sieve segregation test [%] | Compressive strength test [MPa] | |
|---|---|---|---|---|---|
| | | | | $CS_7$ (7 days) | $CS_{28}$ (28 days) |
| $SCC_0$ | 761 | 0.98 | 16.4 | 27.49 | 37.19 |
| $SCC_1$ | 743 | 0.96 | 15.6 | 28.37 | 38.45 |
| $SCC_2$ | 735 | 0.93 | 13.8 | 31.76 | 39.68 |
| $SCC_3$ | 726 | 0.91 | 12.7 | 31.89 | 40.34 |
| $SCC_4$ | 694 | 0.90 | 10.9 | 31.73 | 38.87 |
| $SCC_5$ | 685 | 0.89 | 9.3 | 30.86 | 37.56 |
| $SCC_6$ | 679 | 0.87 | 8.8 | 30.33 | 36.88 |
| $SCC_7$ | 668 | 0.85 | 7.5 | 29.85 | 36.45 |
| $SCC_8$ | 643 | 0.82 | 6.8 | 28.61 | 35.96 |
| $SCC_9$ | 627 | 0.80 | 5.6 | 28.92 | 35.89 |
| $SCC_{10}$ | 612 | 0.79 | 3.2 | 29.12 | 35.16 |

Source: own work.

# Results and discussion

## Fresh concrete results

*Effect of glass powder on slump flow*

The results obtained are presented in Figure 4. They show that all concrete has spreading values located within the field of SCC. The influence of GP on the spreading of concrete is a function of its dosage in all mixtures studied. It can be noted that the more GP content increases, the more the spreading decreases. This can be explained by the fact that the GP amount decreases the granular compactness of the mixes due to its lower fineness than that of the limestone filler. The lack of free water between the particles makes the mixture heavier and thus affects the fluidity, which can reduce the workability of the concrete.

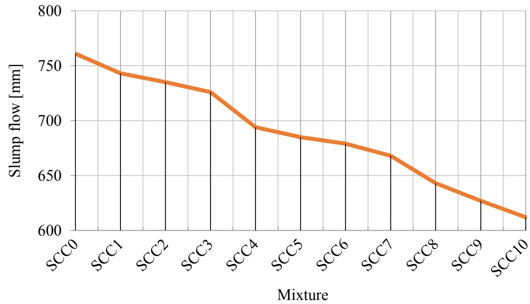


FIGURE 4. Spreading evaluation depending on glass powder filler content
Source: own work.

The GP filler reduces the spreading up to 80.4% [761 mm for SCC0 (0%) and 612 mm for SCC10 (100%)], but it is acceptable because the SCC spreading varies between 550 and 850 mm following the tests to the NF EN 206-9 standard (Afron, 2010b). It is then possible to replace the limestone filler with GP to ensure normalized spreading.

*Effect of glass powder on passing ability (L-box test)*

Figure 5 shows the results of the L-box test. All mixtures give filling rates that fall within the range of SCC, except SCC10, which is formulated entirely with GP filler. These results confirm the interest in increasing the paste volume by adding fines to the composition of SCC. Increasing the GP filler content leads to a linear decrease in the filling rate.

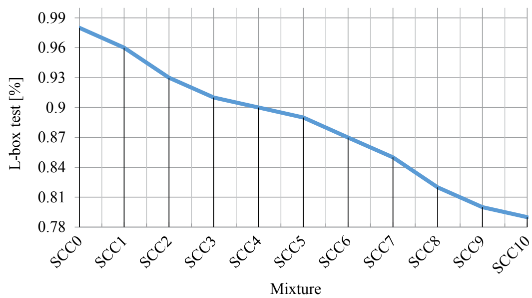


FIGURE 5. Filling evaluation depending on glass powder filler content
Source: own work.

The GP filler reduces the spreading up to 80.6% – 0.98 for SCC0 (0%) and 0.79 for SCC10 (100%) – but remains above 0.8, the limit value defined by the standard tests of the NF EN 206-9 standard (Afron, 2010b). It is thus possible to replace the limestone fillers by (GP) up to 90% to ensure that the filling follows the standards.

*Effect of glass powder on sieve segregation*

The results obtained by the sieve segregation test are shown in Figure 6. All mixtures have a segregation rate that falls within the range of SCC, except SCC0 and SCC1, which are higher than 15%; the other mixtures (from SCC2 to SCC10) have a segregation rate of less than 15%, thus confirming good stability.

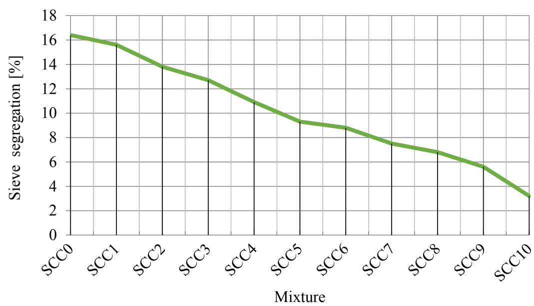


FIGURE 6. Static segregation depending on glass powder filler content
Source: own work.

It can be noted that beyond the 10% GP filler content, the mixture does not present any risk of static segregation, and concrete based on glass waste (SCC% GP) in an unconfined environment is more stable than concrete based on limestone fillers. These results confirm the interest in increasing the paste volume by adding fines to the composition of SCC.

*Relationship between workability parameters*

The workability of SCC mixes is assessed using slump flow test, L-box test, and the sieve segregation test, as per the NF EN 206-9 standard (Afron, 2010b).

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*Relationship between slump flow and passing ability (L-box test)*

The analysis of Figure 7 indicates that Eq. (1) gives an adequate representation of the actual relationship between slump flow test and L-box test.

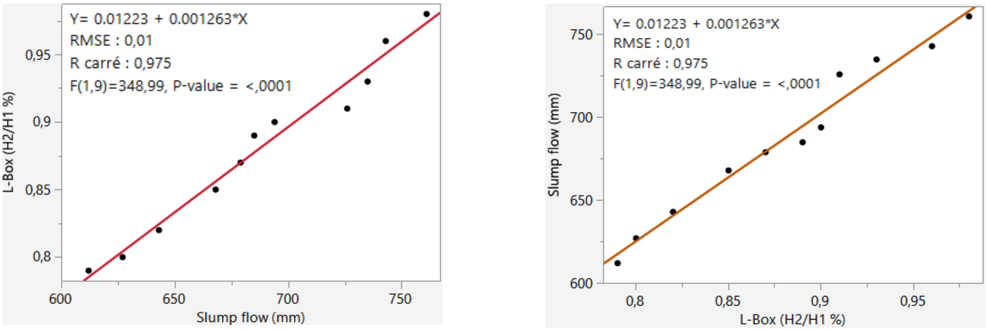


FIGURE 7. Relation between slump flow test and L-box test results
Source: own work.

It is evident from the excellent correlations between the tests. The mathematical models used in slump test and L-box test are given by the following equations:

$$SF = 7.866 + 771.80 \cdot (H_2/H_1),$$

$$H_2/H_1 = 0.0122 + 0.0013 \cdot (SF), \qquad (1)$$

$$R^2 = 0.975.$$

*Relation between slump flow and sieve segregation*

The analysis of Figure 8 indicates that Eq. (2) gives an adequate representation of the actual relationship between the slump flow test and sieve segregation test.

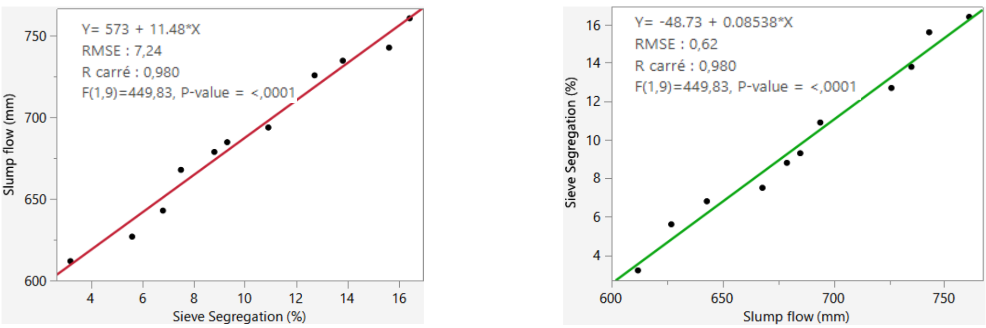


FIGURE 8. Relation between slump flow test and sieve segregation test results
Source: own work.

The mathematical models used in the slump test and sieve segregation test are given by the following equations:

$$SS = -48.73 + 0.0854 \cdot (SF),$$

$$SF = 573 + 11.480 \cdot (SS), \quad (2)$$

$$R^2 = 0.98.$$

*Relation between sieve segregation and passing ability (L-box test)*

Examining Figure 9, it can be seen that Eq. (3) gives an adequate representation of the actual relationship between sieve segregation test and the L-box test.

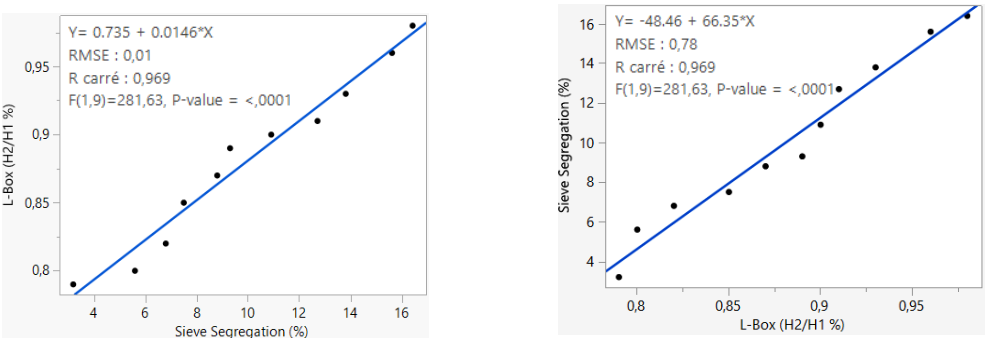


FIGURE 9. Relation between sieve segregation test and L-box test results
Source: own work.

The mathematical models used for the sieve segregation test and L-box test are given by the following equations:

$$SS = -48.460 + 66.350 \cdot (H_2/H_1),$$

$$H_2/H_1 = 0.735 + 0.0146 \cdot (SS), \quad (3)$$

$$R^2 = 0.969.$$

## Recapitulative analysis

Figures 7, 8, and 9 show that SCC (slump flow test, L-box test, and sieve segregation test) parameters have exponential functions with correlation coefficients $R^2 > 0.96$. The ANOVA results show that $P < 0.001$, implying that the coefficients $R$ and adjusted ($R^2_{adj}$) were calculated to assess the adequacy and relevance of the model. The $R^2$ and $R^2_{adj}$ values are close to 1. A positive correlation exists between these parameters that move in tandem; when one parameter decreases, the other parameter decreases, or one parameter increases while the other increases. Because these different variables move in the same direction, they are practically influenced by the same (GP) filler quantity. Despite losing their workability depending on the addition of GP fillers, concrete remains workable; these correlations are in agreement with the results of the study by Roussel (2006).

## Hardened concrete test results

### Effect of glass powder on strengths

The test results obtained for compressive strength after 7 days and 28 days are shown in Figures 10 and 11. The compressive strength curing at 28 days shows that the concrete specimen without GP is 37.19 MPa. Thus, it can be noted that compressive strength grows as the proportion of GP in concrete increases up to 30%. This can be explained by the consumption of portlandite [$Ca(OH)_2$] at around 30% glass powder, which is a crucial component for the pozzolanic reaction, and the production of C-S-H, responsible for mechanical strength (Shi, 2001). In the case of using 10% GP addition, the observed increase is 3.38%; however, for 20% addition, the increase is 6.70%, whereas for an addition of 30% GP, an increase of 8.47% is reached, and that corresponds to the optimum. It has been noticed that compressive strength decreases; in the case of using a 40% addition of GP compared to the optimum, an increase of 4.51% of the initial compressive strength has been observed. The same trend has been obtained for 50% GP content, where an increase of 0.99 is reached.

However, from 60% GP content, a decrease in strength of 0.83% is noticed. When the proportion of GP is up to 70%, a decrease of 1.98% is obtained. However, when this proportion increases to 100%, a decrease in compressive strength of 5.45% is noted, giving a strength value of 35.16 MPa at the end.

Despite these losses in strength, concrete samples still have acceptable strength according to the current standards.

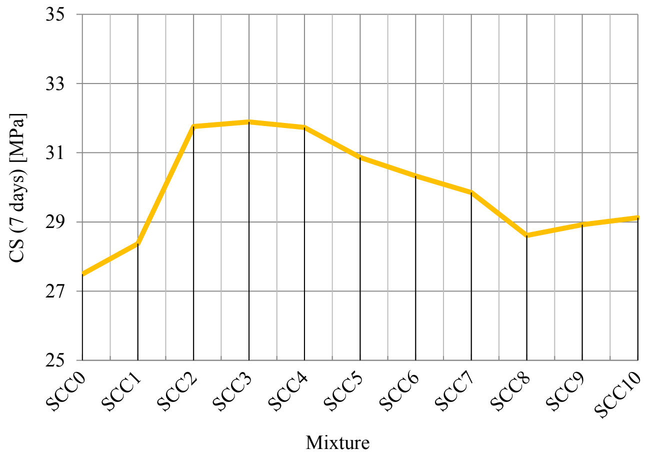


FIGURE 10. Compressive strength at 7 days depending on the GP filler content
Source: own work.

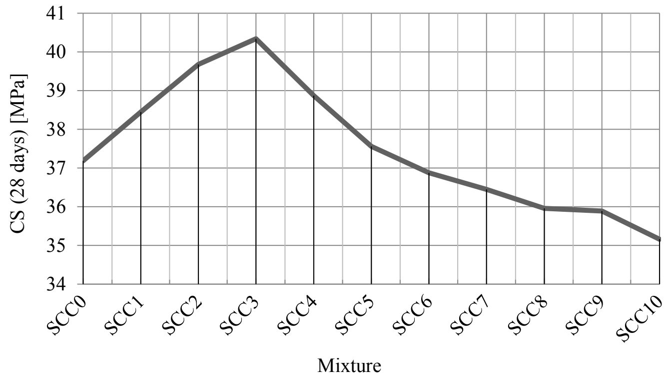


FIGURE 11. Compressive strength at 28 days depending on the GP filler content
Source: own work.

# Conclusions

The main objective of this study was to evaluate the effects of incorporating glass powder (GP) waste, by substituting the filler up to 100%, on the rheological and mechanical properties of self-compacting concrete (SCC). This was achieved through conducting experimental tests and analyzing each formulation, which included varying substitution levels. The following conclusions have been drawn:

- A positive correlation exists between the workability parameters (slump flow test, L-box test and sieve segregation test) due to the obtained results that fall within the range of SCC, except for two mixtures (SCC0 and SCC1 greater than 15%) in the sieve segregation test with a segregation rate of less than 15%. For this purpose, to ensure good concrete workability, the addition of GP filler must exceed 10% incorporation by weight in the replacement of the limestone filler.
- The gain in compressive strength compared to the concrete specimen without GP. The incorporation must be between 10 and 50%, and the optimum remains at 30% with a gain of 8.47%;
- The obtained results showed the advantage of substituting the limestone filler in SCC with GP waste in the same proportions of 10–50%, inducing potential technical interests and environmental benefits;
- The addition of GP can have effects on the fresh concrete by improving stability and eliminating segregation risks about the dosage, whereas for the hardened concrete, substitutions that exceed 50% increase the mechanical strength.
- The gain in strength generated by the addition of GP through the filling and pozzolanic effect, is a durability property that allows us to consider the valorization of the glass in SCC.
- The durability of the improvements made by incorporating GP in cementitious matrix materials needs to be validated through further research, particularly by applying this concrete (SCC) in more challenging environments. Additionally, it is essential to conduct more in-depth investigations into the environmental and economic impacts.

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# Summary

**Valorization of glass powder as filler in self-compacting concrete.** In Algeria, glass waste is underutilized in the industrial sector; however, its potential use in civil engineering offers a significant ecological and economic opportunity. This approach could be a solution to eliminating illegal dumping sites, reduce pollution, and provide a new source of sustainable construction materials. In this context, this research aimed to produce self-compacting concrete (SCC) mixtures using recycled glass powder as a replacement for limestone filler. This research presents an experimental study investigating the impact of glass powder waste as a replacement for the traditionally used limestone filler in self-compacting concrete. To investigate the workability and compressive strength of the SCC studied, eleven concrete mixtures were prepared with varying substitution rates of limestone filler (0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%) with powder glass. The use of powdered glass waste has beneficial effects, as the pozzolanic reaction generates an additional amount of hydrated calcium silicates. The results of the investigation showed an increase in compressive strength compared to the control concrete specimen (without glass powder). The best results were observed when incorporation ranged between 10% and 50%, with the optimal level being 30%, resulting in an 8.47% strength gain. This study contributes to the valorization of glass powder as a substitute for limestone filler. The results demonstrate positive effects on both fresh and hardened characteristics when using glass powder in proportions ranging from 10% to 50% of the filler mass.