

# Effect of waste glass powder as supplementary cementitious material and quarry waste as sand to make eco-friendly SCM

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**Abstract.** This study aims to investigate the effect of incorporating waste glass powder (WGP) and quarry waste sand (QWS) on the properties of eco-friendly self-compacting mortar (SCM). Ordinary cement was replaced with WGP at rates of 0%, 10%, 20% and 30% by weight and the properties of the QWS-based SCM are compared to those of natural sand (NS)-based SCM. In this study, slump flow, superplasticizer requirement, mechanical strength, rheological parameters and hydration heat were investigated. The results obtained show that the use of WGP with different types of sand mixtures increases the fluidity of the SCM. After curing, SCM with 10% WGP exhibited higher compressive and flexural strengths after 28 days for both type of sand. The best performance was obtained with SCM mixes prepared with QWS sand compared to that of NS sand. Adequate relationships have been established to predict slump flow and mechanical strengths as a function of test parameters with high correlation coefficient and low root mean square error.

**Keywords:** eco-friendly; quarry waste sand; recycling; self-compacting mortar; waste glass powder

## 1. Introduction

Self-compacting concrete (SCC) has several technical interests in the field of civil and industrial construction, due to its ability to flow and fill the formwork without any vibration or external energy, even in narrow spaces with congested reinforcements. This offers concrete without segregation or bleeding. The disadvantages associated with this type of concrete are related to its cost, since large volumes of Portland cement and chemical additives are required to ensure better workability (Ouldkaoua *et al.* 2020, Aslani and Ma 2018). SCM is a basic element to develop and design SCC where its study becomes essential to understand and characterize this new concrete. Also, SCM is an economical alternative to cement grout. With its very high fluidity, this product can be used to fill pipes, tunnels, underground tanks or in another repair work (Tuaum *et al.* 2018).

For a successful SCM, its manufacturing must be part of sustainable development and its components must comply with environmental regulations. As cement is the second most used substance in the world after water, the enormous production of this product leads to an unacceptable increase in CO<sub>2</sub> emissions. To mitigate these emissions, the main solution proposed by the International Energy Authority in 2009 (Colgan 2009) was CO<sub>2</sub> capture and storage. In the field of

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construction, another important and well-established strategy to reduce CO<sub>2</sub> emissions is the partial replacement of clinker by other supplementary cementitious materials such as fly ash, slag, natural pozzolan, silica fume, etc. This strategy has the advantage to reduce CO<sub>2</sub> emissions and energy consumption for a clean environment (Moumin *et al.* 2020, Ouldkhaoua *et al.* 2019).

Millions of tons of glass waste are generated globally, and due to its inability to decompose easily, it fills up landfills. However, glass with its siliceous properties, can be used as a supplementary cementitious material in the cement industry or as an aggregate in concrete, promoting sustainable development (Gokulnath *et al.* 2020) and improving concrete quality (Kouassi *et al.* 2020). Rajathi and Portchejian (2014) found that incorporating different amounts of WGP in SCC decreases its rheological and mechanical properties, while Arjun *et al.* (2017) observed an increase in mechanical strengths with WGP contents up to 50%.

The use of sand rich in fines can be considered as an alternative source of fillers. In the production of crushed limestone aggregates, there is a significant proportion of quarry waste which contains 10 to 15% by weight as limestone powder and can be used as sand. Its use in the manufacture of SCC decreases the high demand for fillers, reduces the cost and allows obtaining good physical and mechanical properties such as permeability, water absorption and compressive strength (Benabed *et al.* 2016). However, the quality of high powder sand should be carefully considered before using it in concrete application. In the case of ordinary concrete, the proportion of fines in the sands is generally quite limited where the fraction of fine sand can positively or negatively affect the concrete properties (Topçu and Uğurlu 2003). High powder content from quarry waste sand increases the total surface area of aggregate particles and therefore the mix requires more water to adequately wet the total particle surface area and to maintain specific workability (Nehdi *et al.* 1996, Johansen and Busterud 2001).

The main objective of this study is to perform a suitable mixture design for an eco-friendly SCM composed of WGP and QWS and to analyse some of its properties. An experimental program has been set up to understand the combined action of these two wastes to improve the mortar properties. The combination of these wastes generates a considerable economic gain in the production of mortar and an ecological effect by eliminating both glass and quarry wastes and reducing CO<sub>2</sub> emission.

## 2. Experimental program

### 2.1 Materials

The cement used in this study is a CEM II 42.5 containing 10% limestone powder. Its Blaine specific surface is 3250 cm<sup>2</sup>/g. Glass waste was collected from public landfills, broken into small pieces and introduced into a disc crusher to transform it into fine sand. Finally, a ball mill is used to obtain a very fine powder with a fineness of 4100 cm<sup>2</sup>/g. This powder is used as a cement substitute in the preparation of a self-compacting mortar. The chemical compositions of these two materials are presented in Table 1. Two types of sand were used in this study; natural sand (NS) and quarry waste sand (QWS). The physical properties of these sands are given in Table 2. The gradation curves of NS and QWS used are illustrated in Fig. 1. SN sand appears fine and uniform with smooth grains; on the other hand, the rough grained QWS sand is not very coarse and contains 12% of fine particles less than 80µm, which offers an advantage for obtaining SCM. Polycarboxylate superplasticiser (SP) with a specific gravity of 1.07 and a solids content of 30% was used in SCM mixtures to achieve the desired fluidity.

Table 1 Characteristics of cement and glass powder used

	Ordinary cement	Waste glass powder
Chemical composition (%)		
SiO <sub>2</sub>	22.6	72.8
Al <sub>2</sub> O <sub>3</sub>	4.2	1.28
FeO <sub>3</sub>	3.55	0.09
CaO	62.17	8.15
SO <sub>3</sub>	2.19	0.22
MgO	0.63	4.1
K <sub>2</sub> O	0.42	0.48
Na <sub>2</sub> O		12.4
TiO <sub>2</sub>		0.47
PAF	1.84	
Mineralogical composition (%)		
C <sub>3</sub> S	41.8	
C <sub>2</sub> S	33.3	
C <sub>3</sub> A	5.1	
C <sub>4</sub> AF	10.7	
Physical properties		
Blaine fineness (cm <sup>2</sup> /g)	3250	4100
Specific gravity	3.1	2.61

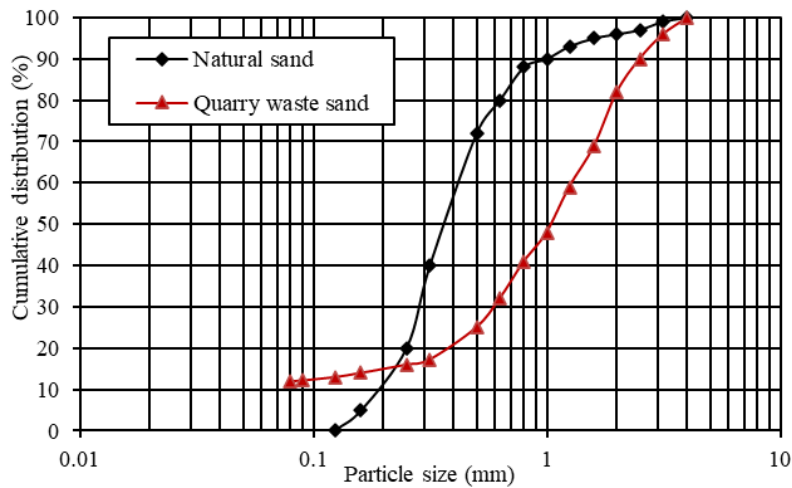


Fig. 1 Particle size distribution of NS and QWS used

### 2.2 Mixture proportion and test program

The composition of the different SCMs is based on an approach based on the optimization of the volume of sand to achieve suitable fluidity, as outlined by Okamura and Ouchi (2003). Slump flow

Table 2 Physical properties of sands used

Characteristics	NS	QWS
Fineness modulus	1.86	2.95
Sand Equivalent (%)	86	76
Specific weight (kg/m <sup>3</sup> )	2650	2670
Bulk density (kg/m <sup>3</sup> )	1395	1477
Compactness	53	55
Water Absorption (%)	1.8	2.1

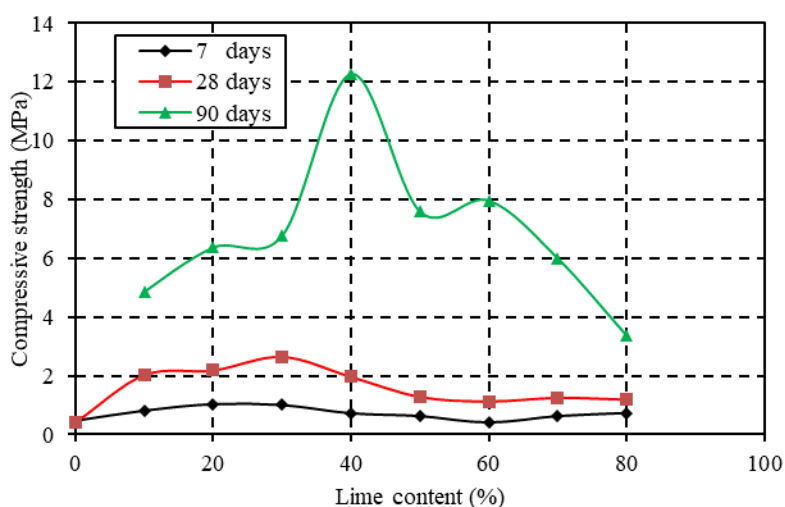


Fig. 2 Compressive strength of mortar composed with WGP and different lime content

test of fresh SCM was used to determine for each sand/mortar (S/M), water/binder (W/B), WGP/binder ratios and superplasticizer (SP) dosage responding to the requirements of SCM. For an SCM mortar composed of a volume of cement, sand, water, WGP, air content and superplasticizer, it is always necessary to seek the proportions which give better mortar quality. The quality of each SCM is based on the results of the mini-cone spread test. The recommended slump flow target values for performing SCM are between 24 mm and 26 mm, as suggested by EFNARC (2002). In this study, a higher slump capacity was targeted with a slump flow between 270 mm and 330 mm, which is acceptable by Domone and Jin (1999) recommendations. The properties required for SCM to be considered self-compacting are its high fluidity and sufficient segregation resistance. The resistance to segregation is visually checked by the non-separation of the liquid from the aggregate mixture during the mini-cone spread test. During all the tests carried out, no segregation was observed.

### 2.3 Mixing procedure

The mixing procedure was to mix the cement, the glass powder and the sand for 1 minute to obtain a homogeneous mixture. Then 70% of the mixing water was added with a regular flow for 1 minute. Finally, the remaining mixing water with the requirement amount of superplasticizer were added for another 1 minute. The mixing procedure continued for 5 minutes.

## **2.4 Test methods**

The filling capacity of the SCM was evaluated by the slump flow test. The slump test involves filling the mini cone placed on a flat surface, and as the mold is lifted, the diameter of the spread mortar is measured in two perpendicular directions. The spread mortar was visually checked for any segregation or bleeding to achieve continuous flow without increasing the flow time as mentioned by EFNARC (2002). The rheological parameters are measured using a mortar rheometer which shears the fresh mortar with a vane 15 cm high and 10 cm wide. An acquisition system measures the total friction torque for each imposed rotation speed of the vane (Adjoudj *et al.* 2014). The yield stress and the plastic viscosity can be estimated from the curves of shear stress as a function of the shear rate by regression analysis according to Bingham's relationship.

A semi-adiabatic calorimeter was chosen to measure the hydration heat of the mortar samples in accordance with the EN 196-9 (2010). The hydration heat of the mortar was the combination of the accumulated heat in the calorimeter and the heat dispersed in the environment. The hardened properties of SCM were estimated by performing flexural and compressive strength tests. Flexural strength and compressive strength are measured after 1, 3, 7, 28 and 90 days, according to BS EN 196-1 (2016) recommendations. Strength measurements beyond 28 days can highlight the pozzolanic activity of WGP.

## **3. Research of mix composition**

### **3.1 Activation of waste glass powder**

The first part of this work is to examine the effect of WGP activation using hydrated lime for its effective use as a pozzolan material in mortar. To check the pozzolanic activity of glass powder, mortars were made with powder glass-sand-water mass proportions of 1:3:0.5. Glass powder was replaced by different rates with lime by adding suitable proportions of superplasticizer to keep the same consistency of the mortar. According to the obtained results illustrated in Fig. 2, there is a gain in strength when the mortar contains lime with glass powder. After mixing, the dissolution of the lime raises the pH of the interstitial solution and makes it basic, which triggers the pozzolanic activity of the glass powder. This pozzolanic reaction leads to the production of hydration products similar to those obtained by the cement hydration. At 90 days, the strength mortar reaches 12 MPa when 40% of glass powder is replaced with lime. This rise in compressive strength testifies to the pozzolanic activity of the glass powder and encourages its use as cementitious materials to eliminate this waste and to obtain eco-friendly cement.

### **3.2 Optimization of sand content in mortar**

The SCM is composed with proportions of sand and cement paste to achieve a fluid consistency. For a given volume of mortar, the optimum quantity of sand is targeted in order to guarantee the economic conditions, and then the superplasticizer dosage is adjusted. The adjustment aims to achieve a flowable mortar with a spread between 270 and 330 mm, as recommended by Domone and Jin (1999).

As shown in Fig. 3, SCM can be formulated with NS or QWS. It is clearly seen that QWS is more efficient compared to NS sand where up to sand to mortar ratio of 0.55 can be used without

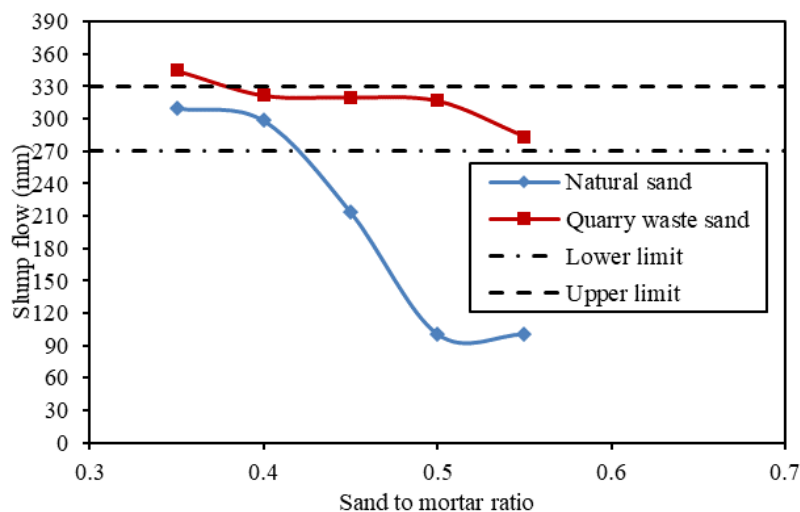


Fig. 3 Slump flow of SCM mixtures with different sand to mortar ratio

any segregation or bleeding. When the mortar is made with natural sand, only 40% sand can be incorporated into the mix but when QWS is used, the sand content can increase and provide more mortar economy. This different effect of these two sands on the properties of SCM may be due to the nature, shape and size of the grain particles (Sahraoui and Bouziani 2019).

This result agrees with that of Benabed *et al.* (2016) which reported that the rheological properties of SCC are improved for mixtures containing crushed sand. Moreover, the fresh state of the SCCs by combining sands of varied grain size indicates a better behaviour (Rmili *et al.* 2009). Sua-iam and Makul (2013) used limestone sand to improve SCC properties and noticed an increase in slump rate with increasing sand content in which 60% rate gives the best fluidity compared to others mixtures. The limestone fillers content in QWS has a great dispersive power that made mortar more fluid evenly with high sand content. Bounedjema *et al.* (2017) state that limestone powder containing in QWS contributes to reduce the inter-particle friction in fresh paste, increase the packing density and thus reduce the volume of filling water.

### 3.3 Optimisation of superplasticizer dosage

Once the sand content in the mortar is determined, the dosage of superplasticizer is varied and the corresponding spread is measured each time. Two sets of mortars were made one based on 40% NS and the other 55% QWS where each set was mixed with W/C ratios of 0.4, 0.5 and 0.6. According to the results obtained in Fig. 4, it turns out that the type of sand plays a key role to make a SCM. To have a spread greater than 270 mm with NS, a superplasticizer dosage of 0.8%, 0.52% and 0.28% was required for W/C ratios of 0.4, 0.5 and 0.6 respectively. When the mortar is based on QWS, these dosages rise to 0.96%, 0.66% and 0.44% for the same W/C ratios. This increase is due to the decrease in cement paste volume caused by the high rate of QWS. So, it may be concluded that the use of QWS in SCM exhibits better fluidity with acceptable superplasticizer dosage and smaller cement content. This SCM seems more economic than that with NS sand.

QWS is a material rich in fines which effectively contributes to the development of self-compacting mortars. Its high rate in the formulation requires compensation by an additional dosage

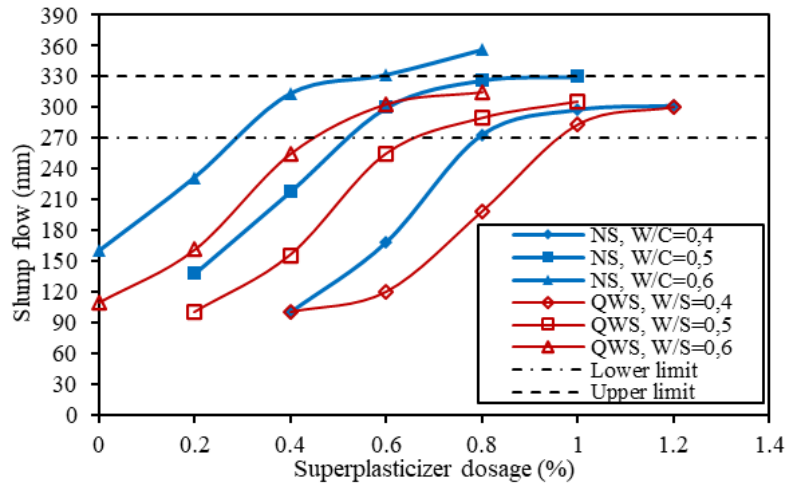


Fig. 4 Slump flow of SCM mixtures based on NS and QWS sands for different W/C ratios

Table 3 Mix proportions of SCM made with various type of sand

Mixtures	W/B	$V_{WGP}/V_B$ p	S/M	Sand (kg/m <sup>3</sup> )	Cement: (kg/m <sup>3</sup> )	WGP (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	Superplasticizer (%)
NS-0-0.4	0.4	0	0.4	1060	802,7	0,0	321,1	1.0
NS-10-0.4	0.4	0.1	0.4	1060	728,8	68,2	318,8	1.0
NS-20-0.4	0.4	0.2	0.4	1060	653,6	137,6	316,5	1.0
NS-30-0.4	0.4	0.3	0.4	1060	577,0	208,2	314,1	1.0
NS-0-0.5	0.5	0	0.4	1060	705,1	0,0	352,5	0.6
NS-10-0.5	0.5	0.1	0.4	1060	640,7	59,9	350,3	0.6
NS-20-0.5	0.5	0.2	0.4	1060	575,1	121,1	348,1	0.6
NS-30-0.5	0.5	0.3	0.4	1060	508,2	183,4	345,8	0.6
NS-0-0.6	0.6	0	0.4	1060	628,7	0,0	377,2	0.4
NS-10-0.6	0.6	0.1	0.4	1060	571,7	53,5	375,1	0.4
NS-20-0.6	0.6	0.2	0.4	1060	513,5	108,1	372,9	0.4
NS-30-0.6	0.6	0.3	0.4	1060	454,1	163,8	370,7	0.4
QWS-0-0.4	0.4	0	0.55	1468,5	595,1	0,0	238,0	1.2
QWS-10-0.4	0.4	0.1	0.55	1468,5	540,3	50,5	236,3	1.2
QWS-20-0.4	0.4	0.2	0.55	1468,5	484,6	102,0	234,6	1.2
QWS-30-0.4	0.4	0.3	0.55	1468,5	427,8	154,4	232,9	1.2
QWS-0-0.5	0.5	0	0.55	1468,5	522,7	0,0	261,4	0.8
QWS-10-0.5	0.5	0.1	0.55	1468,5	475,0	44,4	259,7	0.8
QWS-20-0.5	0.5	0.2	0.55	1468,5	426,4	89,7	258,1	0.8
QWS-30-0.5	0.5	0.3	0.55	1468,5	376,8	136,0	256,4	0.8
QWS-0-0.6	0.6	0	0.55	1468,5	466,1	0,0	279,7	0.6
QWS-10-0.6	0.6	0.1	0.55	1468,5	423,8	39,6	278,1	0.6
QWS-20-0.6	0.6	0.2	0.55	1468,5	380,7	80,1	276,5	0.6
QWS-30-0.6	0.6	0.3	0.55	1468,5	336,6	121,5	274,9	0.6

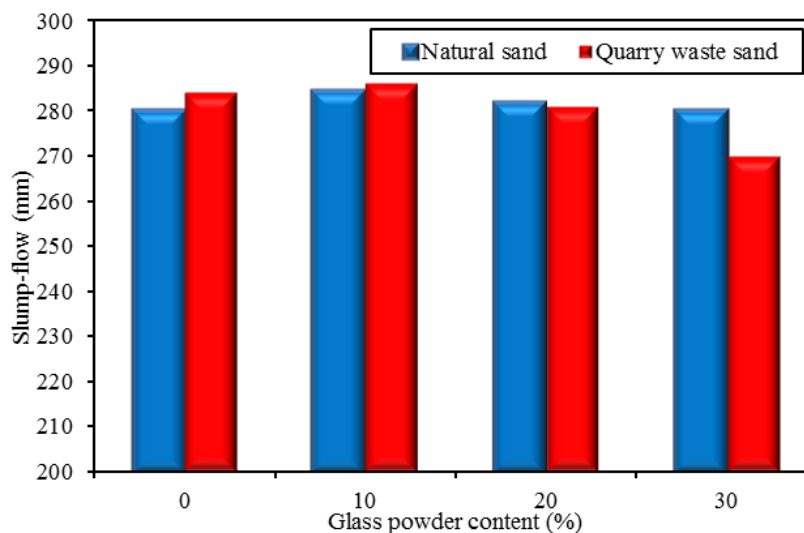


Fig. 5 Slump-flow of different SCM mixtures with water to cement ratio of 0.5

of superplasticizer. This is in agreement with others results (Benabed *et al.* 2012) where mortars based on mixed sand (crushed + natural) have good fluidity. Similarly, Sua-iam and Makul (2013) noticed that replacing natural sand with crushed sand improves the passing ability of self-compacting concrete.

### 3.4 Mixture proportion

To study the effect of WGP on the properties of SCM, two set of mortars are prepared. The first one with NS sand based on 40% sand content by volume and the second is QWS-based mortar having 55% of sand content by volume. Each group has similar fluidity in which 10%, 20% and 30% volume of cement is substituted by WGP. To keep the same slump flow for all mixtures, 1%, 0.6%, and 0.4% superplasticizer were added to the first set and 1.2%, 0.8, and 0.6% superplasticizer were added to the second set when mixed with water to cement ratio of 0.4, 0.5 and 0.6 respectively. The mixture proportions are given in Table 3.

## 4. Results and discussions

### 4.1 Effect of glass powder on slump-flow

The effect of glass powder on mortar flow for each type of sand is shown in Fig. 5. From these results, the values of slump-flow as a function of glass powder content for all mixtures tested varie between 270 mm and 286 mm, which is acceptable by Domone and Jin (1999) recommendations. All samples examined will represent mixtures without segregation and bleeding. It can be concluded that the presence of WGP in the SCM formulation slightly affects the fluidity of the mortar where a rate of 10% seems to provide a weak improvement.

This is consistent with the findings of Ahmad and Zhou (2023) that the flow of self-compacting concrete improves with increasing the proportion of WGP. The smooth glass particles act as

lubricants inside the mortar, minimizing internal friction, facilitating its flow and leading to more filling ability. This may also be due to the presence of fine particles in QWS sand or in WGP which gives a gain in fluidity to the SCM. This was also observed by Miyazawa *et al.* (2009) where fluidity and resistance to segregation increased with decreasing particle size. Beyond 20% content a slight decrease in mortar flow is noticed, especially when mortar is made with QWS. This decrease in flow with increasing WGP content can be attributed to the low density of glass relative to the density of cement (Rehman *et al.* 2018). In the same context, it is noticed that the flow of SCM varies according to each type of sand and WGP substitution rate. For mortar mixed with 10% WGP, the spread reaches 284 mm and 286 mm for NS and QWS sand respectively. This can be explained by the presence of fines in QWS which gives a gain in fluidity to mixtures.

In the same way, Benabed *et al.* (2012) examined the influence of various combinations of sand types on the rheological behavior of SCM and found that SCM based on crushed sand achieves a slump of 263 mm. This result can be improved to 289 mm for a mortar mixed with 50% crushed sand and 50% NS and reduced to 232 mm for a mix made with 50% crushed sand and 50% dune sand. This is due to the finesses of dune sand with finesses modulus of 0.78 which requires high water demand in order to achieve the same fluidity. When NS is combined with other sands, it can improve the slump flow due to its smooth and rounded grain texture. On the other hand, when crushed sand is used in mortars, the rheological parameters may increase due to the interference between the rough and elongated particles of this sand compared to the smooth and spherical particles of NS. In addition, some rheological parameters start to increase linearly at fines contents greater than 16% (Westerholm and Lagerblad 2008), in this study the QWS contains only 12%. Although workability increased with the inclusion of WGP, no segregation was observed. Das *et al.* (2024) qualified this phenomenon by the reduction of deformation of the WGP-based mixture which improves the viscosity by maintaining a uniform particle suspension.

Deepa *et al.* (2022) also observed an increase in slump with an increase in the WGP content; this increased workability may be due to the anti-adhesive surface of glass powder, its low affinity toward water or its slow hydration. Also, it is noticed that the increase of the substitution rate of cement by WGP increases concrete slump where each 5% of glass powder cement replacement decreases water requirement by 0.4% (Aliabdo *et al.* 2016). The low water demand propriety of this material results in high workability and can help to improve the strength (Sobolev *et al.* 2007). The fine particles of recycled glass filled the empty voids between the larger particles of sand which leads to releasing excess water to improve workability. Also, this positive effect on workability may be due to the glassy surface and low water absorption of glass powder or may be attributed to the size particles of glass powder compared with cement (Aliabdo *et al.* 2016).

#### 4.2 Variation of rheological parameters

The rheological behaviour of mortars containing glass powder is influenced by the amount of mixing water. Tests are carried out on the various mortars with a rheometer in the laboratory. By imposing a speed profile on the rheometer, the torque is measured with and without mortar. The calculation steps followed are based on the approach presented by de Estellé and Lanos (2008). From the variation of the torque and the corresponding rotational speed, the rheological parameters are deduced.

According to the obtained results, it will be noted that the values of the yield stress of the various mortars with or without glass powder are very low. This is consistent with the behaviour of self- of superplasticizer compacting mortars which require no vibration for pouring. Plastic viscosity

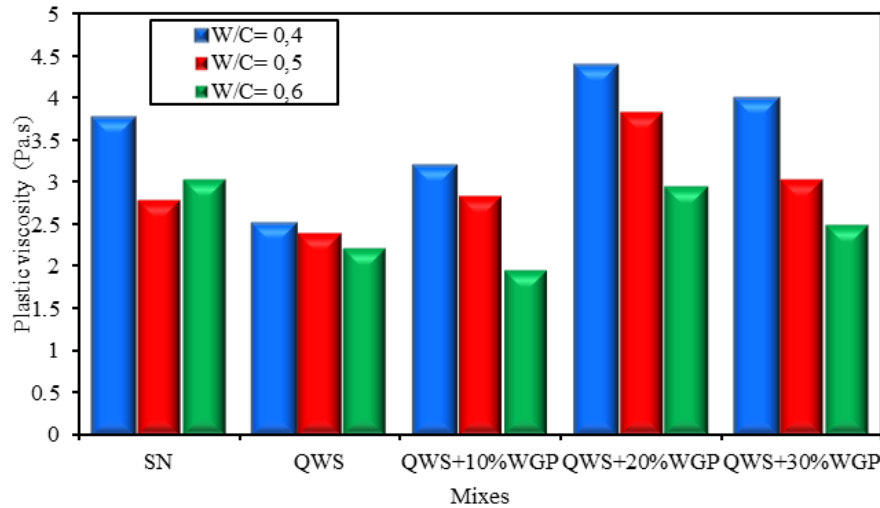


Fig. 6 Plastic viscosity values obtained from SCM containing different WGP for three W/C ratios

values are shown in Fig. 6 where a mixture with a high W/C ratio decreases the viscosity especially for mortars rich in glass powder. The substitution of cement by glass powder makes the mortar more viscous, in particular close to a rate of 20%, beyond which a fall caused by a dilution effect is observed. For a high WGP content, the water available for the hydration of the cement is abundant and the mixture behaves as in a high W/C ratio followed by a decrease in viscosity values. As seen in Fig. 6, the finesse of glass powder was higher than that of ordinary cement and hence more water was required to cover all particles surfaces. This leads to viscous mortar. Moreover, some previous findings (Li *et al.* 2020, Yin *et al.* 2021) indicate that the use of glass powder as cement replacement decreased yield stress and plastic viscosity caused by the low reactivity of this material at the early age conditions.

The rheological behaviour of mortars indicates that the morphology of the sand used has a significant impact on its rheological properties (Li *et al.* 2023). This can be attributed to the coupled effect of packing density, specific surface area and paste film thickness (Li *et al.* 2023, Adjoudj *et al.* 2018). By its large fine fraction, QWS sand has a strong effect on the rheological properties of the mortar, where it has been confirmed by other works (Cepuritis *et al.* 2016) that the fraction below 0.125 mm has 6 to 8 times more effect on the rheology of concrete. It is evident to show that the QWS-based mortar has lower rheological parameters than the NS-based mortar. This decrease can be explained by the quantity of limestone powders present in QWS which fill the deficit in fine grains. Their contribution to improving the workability and rheological parameters of the mortar is linked to the w/c ratio used. This is consistent with some research (Boundedjema *et al.* 2017) which showed that yield strength and plastic viscosity were reduced by 23% and 28% when using QWS instead of NS. Due to the grain shape of sand, the yield strength and plastic viscosity of mortar prepared with crushed sand can be 1.57 and 2.38 times higher than those of NS sand (Li *et al.* 2023).

#### 4.3 Effect of glass powder on flexural strength

Figs. 7 and 8 illustrate the variation on flexural strengths of various mixtures obtained at 1, 3, 7, 28 and 90 days. From these results, all flexural strength increase with age. QWS sand-based mortars

exhibit flexural strengths 1.3 to 1.6 times higher than NS sand-based mortars. It is clear that the incorporation of WGP into the SCM formulation results in decreased strength, except for 10% WGP content and at late age. When the SCM is based on NS, the glass powder has a negative effect on the flexural strength as shown in Fig. 7. At 90 days, SCM with 10% WGP content has 5% higher flexural strength than SCM without WGP for both sands used. This late WGP activity confirms the results found in the WGP activity part. SCM made with QWS retains flexural strengths close to those of a reference mortar designed without WGP as shown in Fig. 8. As the WGP rate increases, decreases in flexural strength are observed. For an optimal rate of 10%, markedly high strength is observed at certain ages. This shows an activity of this substance under certain conditions. From the third day, it is noted that 10% of WGP brings a marked improvement in the flexural strength. For this WGP content, flexural strength decreases by 10% for NS sand based mortar, but this decrease is only 5% when using QWS sand. This improvement is retained for advanced ages. When this rate is exceeded, drop-in strength is particularly noticeable for advanced ages. At one day age, a 50% strength decrease was recorded for mortars containing 30% WGP for both sands used. After 28 days of curing, this decrease was reduced to 30% and 20% for SCMs made with SN and QWS respectively.

According to these results, it is noticed that the tendency of the flexural strength of SCM mixtures is related to the type of sand used. For example, the flexural strength with QWS is higher than that with natural sand. Benabed *et al.* (2014) found that the use of calcareous sand with siliceous sand has a positive effect on the mechanical strengths. At early age (1 day), the SCMs retain flexural strengths similar to those of the reference mortar up to a rate of 20% WGP. Beyond 7 days of hardening, drop-in strength is observed for all types of sand. This decrease in the flexural strength of SCM with WGP is explained by the presence of poor adhesion between WGP and the cement matrix, where failure is triggered when the load is applied. This pattern of reduced flexural strength has been detected in several previous results (Gokulnath *et al.* 2020, Vanjare and Mahure. 2012). In the same context, Kadik *et al.* (2020) found that substituting 20% or 30% of cement with WGP does not affect the long-term tensile strength development where all mixes achieve the same tensile strength of about 7.8 MPa. Also, a reduction in flexural strength of 2%, 3.7% and 6.75% were observed for WGP content of 5%, 10% and 15% respectively (Vanjare and Mahure, 2012). At 28 days, the strengths recorded are 8.5 MPa and 8 MPa when using QWS or NS sand respectively (Gokulnath *et al.* 2020). Li *et al.* (2011) carried out a comparative study on the mechanical performance of concretes made from crushed limestone sands and concretes made from alluvial sands. The results show an improvement in the flexural strength of the mixtures with crushed sands. This is explained on the one hand by the angularity of crushed sand, which ensures good adhesion between the grains and the cement matrix, and on the other hand by the existence of micro-fines which fill the microspores, leading to a densification of the microstructure of the cement paste (Wakchaure *et al.* 2012).

Also, the low level of pozzolanic reaction of the WGP used remains low to compensate for the quantity of substituted cement. According to the results of thermogravimetric analyses, the mortar containing 20% WGP presents a decrease of 9.9% in the CH content and an increase of 42.6% in the CSH gel content between 28 days and 90 days of curing resulting from a secondary hydration between WGP and CH (Qiong *et al.* 2022). Similarly, Kadik *et al.* (2020) showed that concretes with 20% and 30% WGP have 34% and 43% lower CH content compared to the control concrete without WGP. Indeed, WGP consumes the portlandite produced by the hydration of cement to form CSH by a pozzolanic reaction. This pozzolanic activity remains linked to the composition of the glass and its fineness where the WGP used in this study turns out to have low pozzolanicity.

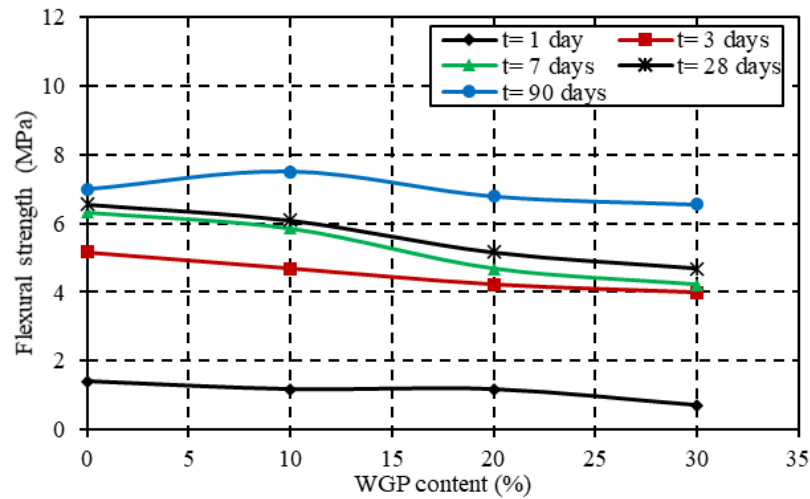


Fig. 7 Flexural strength of the different SCM mixtures made with WGP and NS

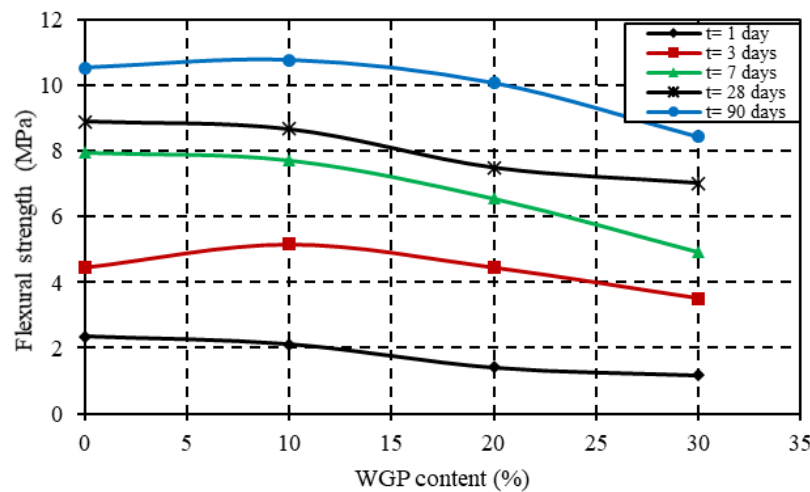


Fig. 8 Flexural strength of the different SCM mixtures made with WGP and QWS

#### 4.4 Effect of glass powder on compressive strength

Figs. 9 and 10 show the results of compressive strength for different mixtures. It can even be seen from these results, that the substitution of different levels of cement by WGP generates a slight reduction in the compressive strengths at early age. At three days, the SCM gives drop-in strength of 14%, 26% and 45% for mortars containing 10%, 20% and 30% of WGP respectively. At 90 days, the presence of WGP gives an increase in compressive strength compared to the control mortar. When 10% of cement was replaced by WGP, the compressive strength increased from 48 MPa to 49 MPa for NS sand-based SCM and from 52 MPa to 55.2 MPa for QWS sand-based SCM. This improvement at long-term compressive strength is caused by the pozzolanic activity of this substance which becomes active after the saturation of the interstitial solution by the lime released by the cement hydration (Rahma *et al.* 2017). Up to a rate of 30% there was 8% decrease in

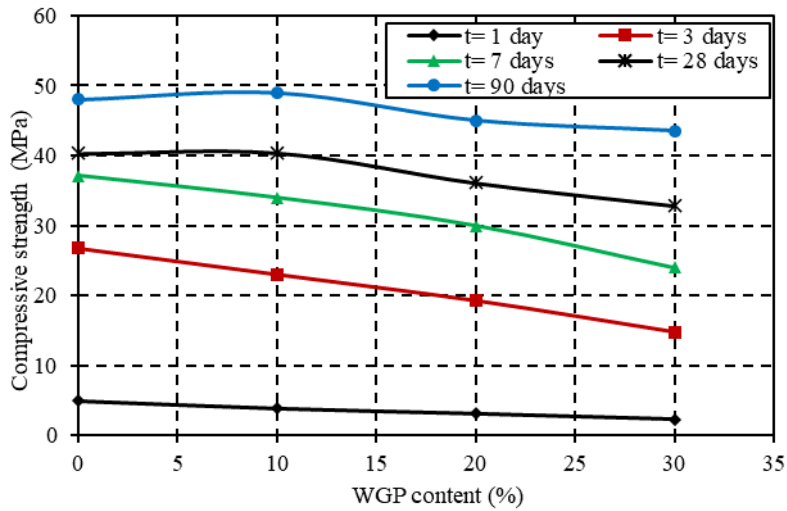


Fig. 9 Compressive strength of the different SCM mixtures made with WGP and NS

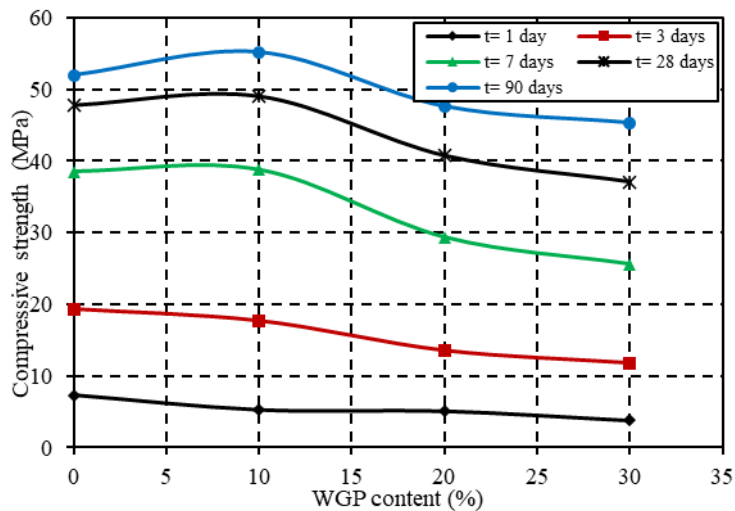


Fig. 10 Compressive strength of the different SCM mixtures made with WGP and QWS

compressive strength attributed to cement dilution for higher levels substitution (Ouldkaoua *et al.* 2020).

Similarly, reductions in compressive strength of 14.7% (Das *et al.* 2024) and 21% (Salahaddin *et al.* 2024) were observed between the control concrete and that containing 30% WGP. After 90 days of curing, the results of Kadik *et al.* (2020) show a decrease of 4.9% and 16% in the compressive strength of concretes containing 20% and 30% WGP, respectively, compared to the control mix. In other results, a general trend was observed with increasing WGP content, a 21% decrease in compressive strength up to a content of 10% followed by an increase in 23% when the WGP content increases from 10% to 20% (Zhou *et al.* 2024). The best compressive strengths obtained at 90 days are for mixture made with QWS sand. This sand has a

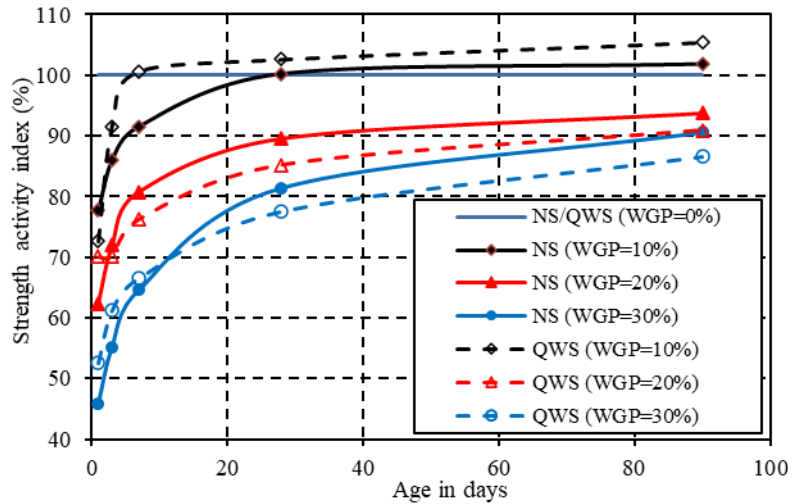


Fig. 11 Strength activity index results versus age for mortar with various WGP content and W/B ratio of 0.5

beneficial effect due to its angular shape which gives a good adhesion cement-aggregate compared to natural sand. In the same way, Kothai and Malthy (2012) show high compressive strength when 30% of natural sand were replaced by crushed sand in SCC.

This result is consistent with previous research (Deepa *et al.* 2022), in which an increase in compressive strength was observed for the WGP concrete specimens with 30% cement replacement. In the same way, Aliabdo *et al.* (2016) found that the use of 10% glass powder as cement replacement enhanced the mortar compressive strength by about 9%. When the content of WGP as cement replacement was fixed up to 15%, the compressive strength of the grouts with 15% WGP was obviously 12% higher than of the reference grouts (Yin *et al.* 2021). Also, best compressive strength values were demonstrated by substitute 50% of cement by glass powder (Aliabdo *et al.* 2016). The low water demand propriety of this material results in high workability and can help to improve the strength (Sobolev *et al.* 2007). These results can be attributed to the formation of additional calcium-silicate hydrate (CSH) of WGP pozzolanic reaction. The CSH gel provides a strong interface transition zone in WGP concrete specimens and increases mechanical strength. When the excessive part of WGP does not have a sufficient part of hydrated CH to produce denser CSH, it plays a role of inert filler, which leads to a decrease of mechanical properties of the matrix.

#### 4.5 Variation of pozzolanic activity index

Based on the compressive strength results, the pozzolanic activity WGP based-mortars can be estimated through strength activity index (SAI) using Eq. 1 following ASTM C618 (2012).

$$SAI(p, t) = \frac{S_c(p, t)}{S_c(0, t)} 100\% \quad (1)$$

where  $S_c(p, t)$  and  $S_c(0, t)$  are compressive strengths of mortar containing  $p$  WGP and without WGP measured at  $t$  age. The results are presented in Fig. 11, in which the SAI varies according to the curing age. The maximum SAI values are observed for 10% WGP substitution after 7 days of curing. The lowest SAI value exhibited at early age and for high substitution rate. Generally, higher

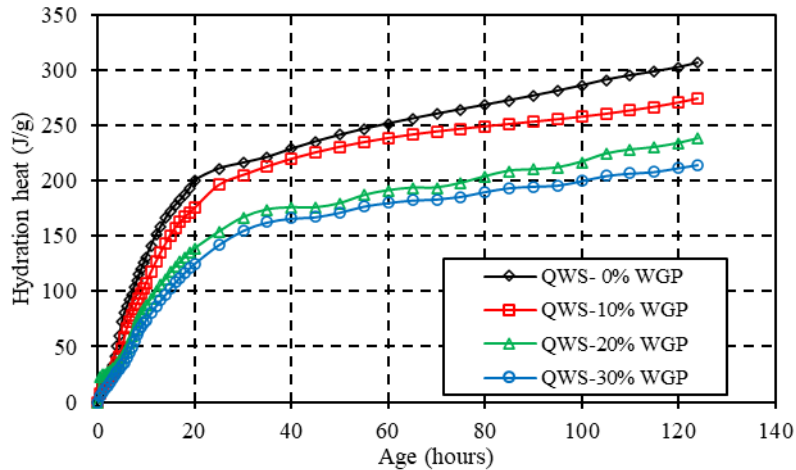


Fig. 12 Evolution of hydration heat of QWS-based mortar containing several WGP contents

SAI values were achieved for 28 and 90 days, which is typical when pozzolanic additions are employed in concrete mixtures.

Fig. 11 illustrates the evolution of this index over time for a mortar produced with a W/C ratio of 0.5; one based on NS sand and the other based on QWS sand. When the cement is replaced by 10% WGP, the SAI index increases rapidly and reaches values greater than 105% from the 7<sup>th</sup> day for QWS based-mortar and after 28 days for NS based-mortar. For high substitution rates, the SAI index remains below 100 even for ages of 90 days and for the two sands used. Mortar made with NS sand reaches SAI values at 90 days of 105%, 91% and 86% for a WGP substitution rate of 10%, 20% and 30% respectively. This index is more significant for QWS based-mortars which reach values of 108%, 98% and 89% for the same rates used. The WGP consisting of amorphous siliceous minerals is very active after the hydration of the cement which increases the concentration of lime. Its pozzolanic reaction is triggered, thus promoting the additional production of CSH which contribute to the hardening of the paste and the increase of strength. According to the obtained results, the SAI values of the entire mixtures meet the ASTM C618 (2012) requirement which proposes an SAI value greater than 75%. In general, higher SAI values were obtained for 28 and 90 days, which is typical when pozzolanic supplementary cementitious materials are used in concrete mixes as the case of WGP. These results support previous findings (Deepa *et al.* 2022, Patel *et al.* 2019).

#### 4.6 Hydration heat evolution

The total hydration heat curves of mortars containing 0%, 10%, 20% and 30% WGP as a cement replacement, cured at  $20 \pm 2^\circ\text{C}$  and mixed with a W/C ratio of 0.5 are shown in Figs. 12 and 13. Also, some characteristic values determined from these curves are summarized in Table 4. According to the curves of cumulative heat of hydration, it appears that the presence of glass powder reduces the heat released by its action of dilution and mainly at early age. As the rate of glass powder increases, the active ordinary cement is diluted in the mixing water and the hydration produces less heat. Over time, the lime produced by the hydration of ordinary cement becomes abundant and conditions become favorable to initiate the pozzolanic reaction of WGP. After five days of

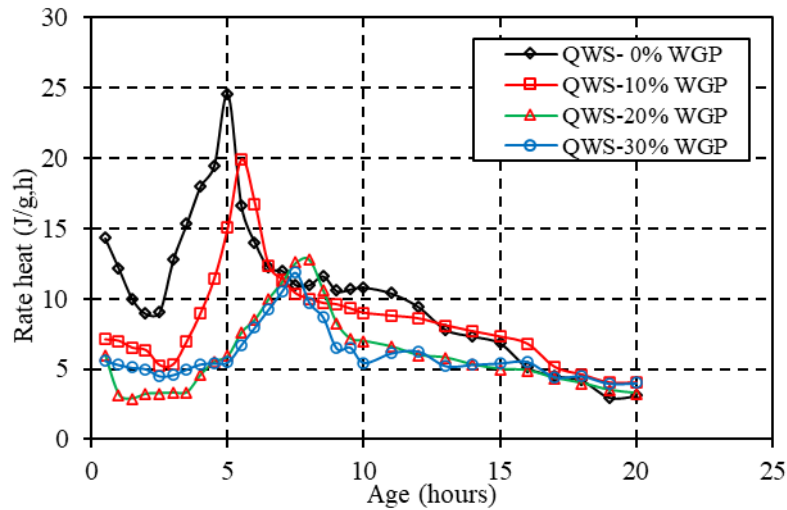


Fig. 13 Evolution of hydration heat rate of QWS-based mortar containing several WGP contents

Table 4 Some characteristic values determined from hydration heat test

Mixture	End of induction period	Second peak emission		Total hydration heat (J/g)				
	Hours	Rate (J/g.h)	Time (h)	1 day	2 days	3 days	4 days	5 days
WGP=0%	2.5	24.5	5	211	241	261	281	306
WGP=10%	3	19.9	5.5	196	230	247	255	274
WGP=20%	3	12.7	8	154	186	198	212	238
WGP=30%	4.5	11.8	7.5	142	171	186	196	214

measurement, the heat released drops from 306 J/g to 214 J/g when 30% cement is replaced by glass powder. Similarly, Chang *et al.* (2015) record 29% less heat during 3 days of the same type of cement.

From the results illustrated in Fig. 13, the glass powder plays a retarding role of the heat of hydration. The intensity of the second peak is reduced and its appearance is delayed. By replacing 20% of cement with glass powder, the second peak is delayed by 3 hours and its value is only half that of a reference mortar. It is shown from the obtained results that the incorporation of the glass powder prolongs the induction period and gives the prepared mortars and concretes additional time for implementation as indicated in Table 4.

## 5. Correlation of the results

### 5.1 Estimation of slump flow variation

For a mortar made with 55% QWS sand, mixed with any W/C ratio and containing WGP, the superplasticizer dosage is determined which gives slumps flow corresponding to SCM. Using a least squares method, a correlation is established between the measured slump flow and that given

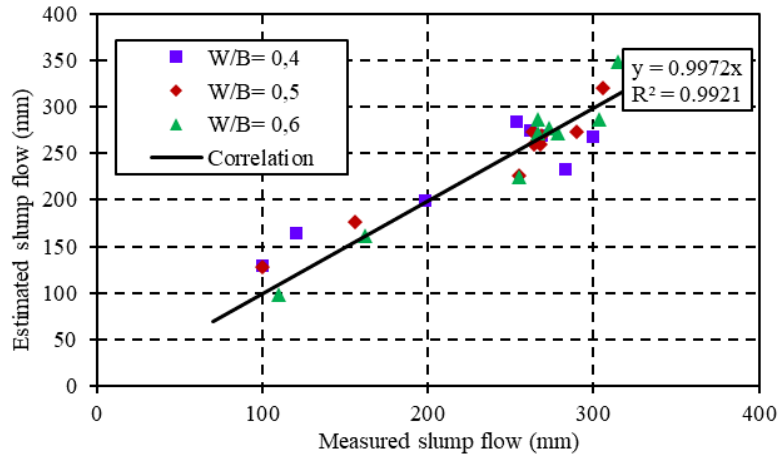


Fig. 14 Comparison between measured and estimated slump flow values using Eq. 2

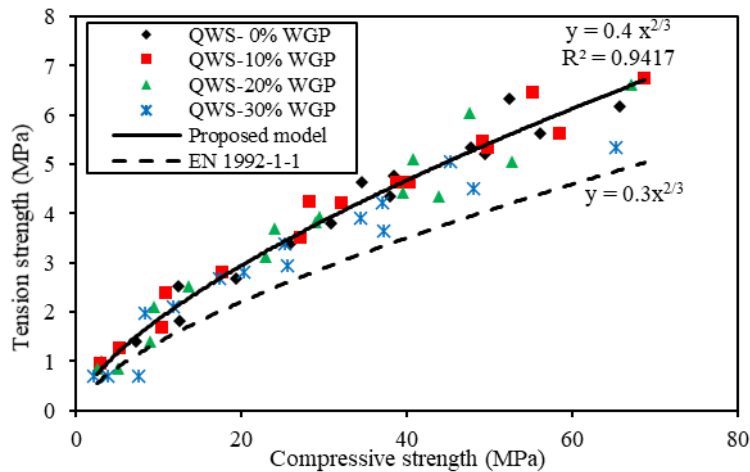


Fig. 15 Comparison between measured and estimated tensile strengths values for mortar based on QWS and WGP

by several relationships according to the different parameters studied. Fig. 14 shows a comparison between the measured values and those estimated by the relation below where the correlation coefficient reaches  $R^2=0.858$  and the root mean square error takes a minimum value of 25 mm.

$$D = 430 (1 + 3.3 Sp - 0.2 Sp^2) \left( 0.5 \frac{W}{B} - 0.06 \right) (1 + 0.54 WGP - 2.2 WGP^2) \quad (2)$$

where D is le slump flow diameter in mm, Sp is le superplasticizer dosage, W/B is the water to binder ratio and WGP is the glass powder content.

### 5.2 Estimation of tension strength

In order to better analyze the variation of the mechanical strength, it is desirable to find a relationship between compressive and tension strength. To do this, it is essential to convert the

obtained flexural strength to tensile strengths. This is possible by introducing a coefficient of 0.6 in order to take into account the plastic phase during the flexural test. Several standards provide simple formulas giving this correlation, such as EN 1992-1-1 (2004):

$$S_t = 0.3 S_c^{2/3} \quad (3)$$

where  $S_t$  and  $S_c$  are tension and compressive strength respectively.

Fig. 15 illustrates the variation of the tensile strength as a function of compressive strength for the three W/C ratios of a mortar based on QWS sand and glass powder. By comparing these results with those given by the model above (EN 1992-1-1 2004), it can be seen that the experimental values exceed those predicted by 1 to 2 MPa. This difference is small for low strength and becomes more important when the strengths increase. This model can be taken up by making corrections to its coefficients to take into account the presence of QWS sand and WGP. The model can be written as follows:

$$S_t = 0.3 S_c^{2/3} \xrightarrow{\text{adjustment}} S_t = 0.4 S_c^{2/3} \quad (4)$$

From this new relationship, it appears that QWS sand plays an important role in the development of tensile strength. These values are 33% higher than those given by the EN 1992-1-1 (2004) model with a correlation coefficient close to unity ( $R^2=0.9417$ ). The root mean square error is only 0.37 MPa while it reaches a value greater than 1 MPa for the EN 1992-1-1 (2004) model.

### 5.3 Estimation of compressive strength

Compressive strength is a property whose equivalence must always be taken into consideration. For this purpose, the Feret model is used to predict the compressive strength of mortar based on glass powder and QWS sand. This model is expressed by the following function called the Feret model:

$$S_c = \frac{K_f}{\left[1 + d_c(1 + y) \frac{W}{C}\right]^2} \quad (5)$$

where W/C is the water to cement ratio,  $d_c$  is the specific gravity of the cement ( $d_c = 3.1$ ),  $y$  is a coefficient depending on the consistency of the concrete ( $y = 0.2$ ) for a fluid consistency (Baron and Olivier 1996) and  $K_f$  is a coefficient depending on the granular skeleton, the class of cement and the presence of any addition.

In order to better analyze the evolution of compressive strength over time, a relationship adopted by ASTM C1074-93 (1993) was used to estimate the properties of concrete according to the maturity approach and which assumes that the hydration kinetics can be expressed by the following equation:

$$S = S_u \frac{t - t_0}{(t - t_0) + t_{50}} \quad (6)$$

where  $S$  is the property of the cement (heat of hydration, shrinkage, strength, etc.),  $S_u$  is its ultimate value,  $t_0$  is the age when the strength begins to develop and can be assimilated to the end of setting time, in this study an average value of  $t_0=0.25$  days can be taken.  $t_{50}$  is the age required to reach 50% of the ultimate value in days (half-strength age).

A general equation can be written as follows:

Table 5 Ultimate strength and half-strength age obtained for all mixtures using Eq. 6

WGP %	W/B	Ultimate strength $S_u$ (MPa)				Half-strength age $t_{50}$ (days)			
		0	10	20	30	0	10	20	30
	0,4	65.49	70.10	67.30	65.70	2.59	3.66	4.54	6.05
	0,5	55.53	58.85	50.73	48.38	4.12	4.96	6.06	7.21
	0,6	39.18	41.93	40.91	36.40	5.03	5.75	7.40	8.93

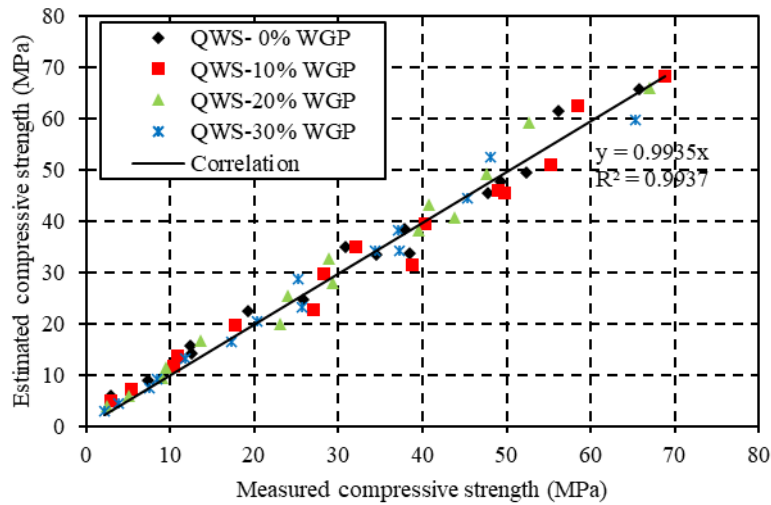


Fig. 16 Variation of measured and estimated compressive strength according to Eq.8

$$S(t) = \frac{K_f}{\left[1 + d_c(1 + y) \frac{W}{C}\right]^2} \frac{(t - t_0)}{(t - t_0) + t_{50}} \quad (7)$$

The correlation of the results by the least squares method makes it possible to estimate the values of the half-strength age  $t_{50}$  and of the ultimate strength  $S_u$  for each rate of WGP and for any water to cement ratio. The obtained results are grouped in Table 5.

According to the results found, when the glass powder replaces part of cement, it brings a gain in strength which takes an optimum value when its substitution rate is around 10%. Despite this low rate, the glass powder is active and by its pozzolanic effect fills the cement deficit and gives the mortar greater performances. Depending on the shape of the variation of the ultimate strength and of the half-strength age, it is possible to test several relationships whose coefficients will be determined by a linear regression of the experimental results. This relationship depends both on the rate of WGP and water to binder ratio and when it is introduced to Feret's formula leads to a general relationship with the following form:

$$S_c \left( t, P_v, \frac{W}{B} \right) = \frac{420(1 + 0.8 P_v - 3.4 P_v^2)}{\left[1 + d_c \frac{W}{B} (1 + y)\right]^2} \frac{(t - t_0)}{7.1 \frac{W}{B} (1 + 3.4 P_v) + (t - t_0)} \quad (8)$$

Fig. 16 illustrates the variation of the measured strengths and those estimated by Eq. 8 where the

correlation coefficient reaches a value of 0.9762, which testifies to the correct choice of this relationship. The mean square error remains below 2.6 MPa on all the results. This relationship is valuable for QWS based-mortar.

## 6. Conclusions

Based on the findings of this experimental study, the following conclusions can be drawn.

- The mortar composed of lime and WGP is active and produces hardened pastes. This proves the pozzolanic effect of this material which promotes its use as supplementary cementitious material.

- The sand content in SCM increases from 40% to 55% when used QWS instead of NS. QWS based-mortar exhibits better fluidity with acceptable superplasticizer dosage and smaller cement content. It seems more economic than that with NS sand.

- The presence of WGP contributes more to improve the workability of NS sand-based SCM than that of QWS sand-based SCM. Substitution of cement with 10% WGP results in an increase in slump flow from 380 mm to 384 mm for NS sand-based SCM and from 384 mm to 386 mm only for QWS sand-based SCM respectively.

- QWS-based mortar has lower rheological parameters than the NS-based mortar. This decrease can be explained by the quantity of limestone powders present in QWS which fill the deficit in fine grains. For high water to cement ratio and 20% WGP content the mortar viscosity is the lowest.

- The presence of WGP delays the release of heat of hydration where the flux curve is more spread out with a smaller peak and a longer dormant period. This makes WGP-based mortar perform better in hot climates and in massive concrete elements.

- Up to 10% of WGP, there is an increase in the mechanical strength at 90 days for the mixtures made with both QWS and NS sands. The best performances were obtained for SCM mixtures prepared with QWS.

- Manufacturing self-compacting mortars from glass waste and quarry waste promises a significant environmental impact. This leads to a potential reduction in natural resource consumption, landfill space savings, use of low-cost materials and reduction of greenhouse gas emissions.

- Mathematical relationships are proposed to express the effect of QWS and WGP on slump flow, flexural strength and compressive strength. The application of the found relationships to the experimental results gives great satisfaction with correlation coefficients close to unity and a low mean square error.

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