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Influence of Fine Sediments on Rheology Properties of the Self-Compacting Concrete

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ABSTRACT

Sediments from dredging works are increasingly used in the building and construction industry. One of the major difficulties of sediment valorization resides notably in the very heterogeneous composition of its fine particles. This paper focused on the rheological impacts caused by the use of uncontaminated raw marine sediment (RS) in Self-Compacting Concrete (SCC). The Densified Mixture Design Algorithm (DMDA) was used to optimize RS as a raw material in the granular structure of the SCC. The AFREM grout method was used to determine the saturation dose of the superplasticizer. The rheological tests were carried out to assess the influence of fine RS particles on the workability of SCC. The stability of SCC was found to be correlated with the high percentage of fine particles less than 125 µm present in the RS. The fine nature of clays and the organic matter caused the increase in yield stress and plastic viscosity. The rheological tests were carried out to assess the influence of fine RS particles on the workability of SCC. The stability of SCC was found to be correlated with the high percentage of fine particles less than 125 µm present in the RS.

Keywords:
Raw sediment
Organic Matter
Clay
Self-compacting concrete
Rheology

1 Introduction

In the 1980's in Japan, the research of specific rheological performance of concrete led to the appearance of self-consolidating concrete (SCC) [1] [2]. Very fluid, homogeneous, and stable the establishment of the SCC is very simplified for every type of application (vertical, horizontal, oblique) [3]. In France, most of the SCC markets is very weak: about 5% against 2% on average in Europe. According to Aloia-Schawartzentruber [3], it explains due to the difficulties of their formulation and the cost of specific materials (mineral additions, superplasticizers, etc.). Utilized to insure the rheological properties. It will be more advantageous to formulate an SCC with reduced cost utilizing secondary raw materials.

In France, more than 50 million cubic meters of marine sediments are dredged every year [4]. According to the regulation context, the management of this huge volume of sediments needs an adapted methodology and treatment processes before considering a valorization at large scale [5][6]. The Dunkirk port in France dredges each year about four million cubic meters. One of the strategic objectives is to find high add-value beneficial uses for large volume of dredged sediments [7]. For more than a decade, several experimental applications with sediments have been performed in public works, road construction, standard concrete and bricks, et. [8][9]. For cementitious materials, the classical approach is to partially replace the sand fraction or the cement fraction. Today, these applications do not yet incorporate optimized sediment rates somehow governed by the question of the environmental impact. In this context, considering the finesse of sediments, their valorization deserves to be studied as a commodity in SCC.

Harbour sediment is a material coming from the erosion of rocks, soils or/and chemical and biochemical precipitations. It is composed of natural and mineral elements (clay, silt, sand), of organic matter (plant debris, micro-organisms, humic colloids), as well as water. The particle size of sediment varies according to the dredging and the treatment process [10]. Silt, clay and a part of organic matter constitute the fine fraction of the sediment (< 63 µm). According to Gosselin [11], this fraction contains more of the contaminated pollutants (heavy metals, micropollutants, nutrients). The sand fraction of the sediment constitutes the largest part. Sand presents a grain size distribution and a porosity close to natural sand 0/2 mm. SCC formulation needs an important volume of paste (cement + superplasticizer + effective water + air), around 330 to 400 l/m³ [12]. This volume of paste allows ensuring the fluidity, homogeneity and stability of the mixture. Nowadays, the most commonly used additions for the formulation of the SCC are calcareous or siliceous additions, metakaolins [2][13]. In

mass, their passing to 2 mm is equal to 100% and greater than 85% of the particles lower than 125 µm [12].

In the state-of-art, many studies have been carried out on the use of treated sediment in cementitious matrix [14]– [18]. For example, Amar et al. have shown that a physical grinding and the calcination of sediment before its use in a cementitious matrix allow to assimilate its behaviour to the one of additions (calcareous, siliceous) and to contribute to improving the mechanical properties of grouts [19], [20]. Rosière et al. [21] have shown that the use of sediment calcined at 650°C in the SCC allows improving the rheological and mechanical properties. To use the sediment in more large quantity of concrete, Agostini et al. [22] have been able to substitute 33% of the sand fraction with sediment in cementitious matrix with a treatment of the sediment according to the Novosol® process.

Thermal treatment of sediment presents some advantages [22]– [31] as:

- the elimination of some of the organic part,
- the improvement of the rheological properties of SCC,
- the removing sediment agglomerates during mixing,
- the obtaining short-term mechanical properties of non-bearing structures,
- the activating of pozzolanic properties in the long term,
- the stabilization of heavy metals.

In this study, for environmental and economic reasons (reduction of the cost of thermal and physical treatment), the valorization strategy was to experiment with the use of sediment in its raw state in the SCC formulation, without the classical mineral additions of this kind of concrete. Chemical analyses of the leaching test on the studied raw sediment concluded that this sediment is a non-inert non-hazardous waste according to the law 28 October 2010/CE. This classification makes it possible legitimately to assume the hypothesis that a physical, chemical and thermal treatment is not necessarily mandatory for the use of sediment in cementitious matrices such as SCC in the present case.

In this paper, the specific case of a SCC formulation incorporating about 300 kg/m^3 of RS with an initial water content of 15 to 20% was tested. The SCC properties in the fresh state give us spreading of SF1 class (550 to 650 mm) and SF2 (660 to 750 mm) according to the classification of the AFGC guideline [12].

It is well known that best rheological properties of SCC are achieved when optimizing parameters such as the compaction index of the mixture, the superplasticizer dosage, the

shape and fineness of the components. The rheological properties of fresh concrete according to Ovarlez and Rossel are often characterized by the Bingham model (Eq.1):

$$\tau = \tau_0 + \eta.\dot{\gamma} \quad (1)$$

Several geometries make it possible to evaluate the yield stress of a simple (simple shear flow) or complex suspension. The most standard geometries used are parallel plates, cones, and plates, quilts. The parallel geometry is used for the measurement of SCC slurry flow. This geometry is suitable for suspensions whose largest elements are less than 200 microns. Its application has advantages such as the use of a small quantity of the paste for the measurements, the free fixing of the height of the gap, and permits to maintain the suspension homogeneity during the measurement of the yield stress while avoiding considering the effects of friction between the suspension and the sidewalls of the geometry [32].

The purpose of this article is to show the experimental feasibility of a SCC with sediment (optimized quantity) and without standard mineral additions. A specific paste rheometer was used to evaluate the impact of the sediment fines fraction on the rheological behavior of the different SCC pastes. Comparisons of yield stress, viscosities, and SEB observations have been realized to quantify the influence of sediment on the SCC mechanical and rheological properties.

2 Materials and protocols

2.1 Materials

- **Sediment characterization**

The raw sediment in its granular composition is not considered a mineral addition. A granular separation of the raw sediment in two fractions (Fig.1.), respectively the passing to 125µm sieve (noted F1) and the refusals to 125 µm sieve (noted F2), shows a difference in properties (physical, geotechnical and mineralogical). The properties of the F1 fraction are closer to the additions used in standard concrete, as shown in Figure 2 concerning the grain size distribution. By experimental feedback about the properties of Dunkirk Port sediments, the F1 fraction approximately stands for 25 to 60% of the raw sediment. This F1 fraction without any treatment can play the role of a mineral pseudo-addition.

The sediments have been dredged from the Grand Port Maritime of Dunkerque (GPMD) located in the North of France.RS is used in the initial water content of 15 to 20% in SCC without any physical or thermal treatment. Leaching tests in electrochemistry allow the pH

evaluation of 8 to 20 ° C. True density was 2.65 g / cm^3 measured by helium pycnometer, which is approximately equal to that of 0/4 natural sand. The methylene blue and size distribution test shows that the RS contains 34.30% clay-silt mixture and 61.47% sand. The organic matter (OM) was measured as 3.33% using the standard XP P94-047 by calcination in an oven at 450 ° C for 3 hours. This conformed to the result of 2.1% of total organic carbon (OC) measured using the standard NF EN 13137 which according to Priby et al. OC / OM must be between 1.4 and 2.5 [33].

The chemical composition of the sediment determined by X-ray fluorescence Table 2 shows that the main chemical elements in the sediment were oxygen containing 52.1%, silicon 28.2%, calcium 10.5% and aluminum 2.9%. The value of PAHs (polycyclic aromatic hydrocarbons) was 6.620 mg / kg and that of PCBs (polychlorinated biphenyls) was 0.55 mg / kg, which was lower than the limited value according to Table 3 of the national decree of 12 December 2014.

RS was used as a secondary raw material in the SCC. Grout particles smaller than 2 mm participated in the mixing. The reconstitution of the granular elements of the SCC paste, the particle size distribution by wet sieving in accordance with XP P 94-041, allowed for a sieve size of 125 µm (fraction F1). Fig. 2. shows the particle size curve of F1, which is close to CEM III / A 42.5. According to the AFGC, the F1 fraction contributes to the volume of the paste and influences the rheological and mechanical properties of the SCC [12]. The technical size distributed by wet sieving allows maintaining the organic matter in the SCC paste and also avoid sediment agglomerates that appear during the drying process. It has made it possible to preserve the shape of the grains of the F1 fraction during rheological measurements.

- **Other Materials**

Slag-blended cement CEM III / A 42.5 N was used to produce SSC in this study. It is composed of 54% clinker and 43% slag-blended. This cement has an alkali content lower than Portland cement and allows the stabilization of traces of heavy metals in the cement matrix. The chemical compositions of this material are given inTable 2. Crushed coarse aggregate (D_{max} 11.2 mm, density 2.45, water absorption capacity 0.43% and unit weight 1389 kg / m3) and natural sand (modulus of fineness 2.71, density 2.64, absorption capacity 1.1% and unit weight 1645.8 kg / m3) were used. Superplasticizer was a high-efficiency polycarboxylate-based with the density of 1.05 g / cm3. This type of high-performance water reducing

admixture (HRWRA) has been used to reduce viscosity and improve workability in different mixtures [34].

2.2 Mixtures' proportioning

The densified mixture design algorithm (DMDA) was applied for concrete mix design to study the feasibility of using marine sediments in SCC [35][36]. DMDA incorporating mineral addition is used to fill the void of aggregates and hence increase the density of the aggregate system. RS used does not partially replace cement or sand but acts physically as filler and creates a nucleation effect for C3A hydrates in the cement paste [37]. The maximum weight ratio α_{max} of blended sand and sediment can be expressed as:

$$\alpha_{max} = \frac{W_{se}}{W_{se} + W_{sa}} \quad (3)$$

Where W_{Se} is the density of sediment in kg/m^3 and W_{sa} is the density of sand in kg/m^3.

The weight ratio β_{max} at the maximum loose, dry density can be expressed as:

$$\beta_{max} = \frac{W_{sed} + W_{sa}}{(W_{sed} + W_{sa}) + W_{ca}} \quad (4)$$

Where W_{ca} is the density of coarse aggregate, kg/m^3.

The minimum cement paste volume (Vp) can be estimated as:

$$V_p = V_v + S * t = nV_v = n(1 - \sum \frac{W_i}{\gamma_i}) \quad (5)$$

Where S is the surface area of aggregates, m^2; t is the thickness of lubricating paste on the surface of aggregate, µm; V_v is the smallest void among aggregates, m^3; W_i is the weight of aggregate, kg/m^3; and γi is the density of aggregate, kg/m^3.

The water-to-binder ratio (W/B) is calculated as following:

$$\lambda = \frac{W_w}{W_B} = \frac{W_w}{W_c + W_{sed}} \quad (6)$$

Two coefficients n were used in the DMDA algorithm to obtain the required workability. The values of n ($n = \frac{V_p}{V_v}$) were 1.164 and 1.189. These values correspond to a W/B ratio of 0.48 and 0.46. Fig. 4.

The grouts were formulated by the AFREM method Fig. 3. [38] They were deduced from that of the concrete by removing all elements larger than 2 mm, together with the water they

absorb. The relationship between SCC and grout by the AFREM grout by the AFREM method is in the hypothesis that the two complex suspensions are linked by their viscosities according to Farris's mode:

$$\eta_{concrete} = \eta_{paste} * f(V_p, CA/FA) \quad (7)$$

Where V_p is the volume of binding paste and CA/FA the coarse/fine aggregate ratio.

The pastes were deduced from that of the grout by removing all elements larger than 125 µm, together with the water they absorb. By making the assumption that the saturation proportion is the same, we can write:

$$\eta_{grout} = \eta_{paste} * f(V_p, CA/FA) \quad (8)$$

The viscosity of the paste is the one that influences the rheological behavior of the grout. Fig. 3. and Fig. 4. illustrates the method of describer used to move from SCC to paste.

2.3 Experiments on Grouts

For each W/B, the proportions of the F1G and F2G grouts are presented in the Table 4. The RS was used in a first state, dried in an oven at 105 ° C to arrive at a constant mass, and a second state where the initial water content of 15% to 20%.

Procedure of saturation of grouts is as follows Fig. 6.

- ✓ The first step of mixing consists of preparing the raw sediment to eliminate as much as possible the agglomerates:
- Introduce into the bowl the sediment and a quantity of water necessary to reach the standard consistency. The standard consistency is measured using the Vicat apparatus equipped with a 10 mm diameter consistency probe as defined in standard NF EN 196 - 3 + A1. This consistency corresponds to the water content of the paste which allows obtaining a penetration of the probe of 30 mm ± 2 mm, that is to say a reading of 10 mm ± 2 mm. The water demand for the RS evaluated according to the standard NF P 18 – 508 is 28.5%.
- Mix at high speed for the 60s.
- Mix in slow speed for 15s while introducing passers to 2 mm of natural sand 0/4.
- Mix for 45s at high speed. During this period, the sand grains will shear the maximum agglomerates of RS, this is a point that will be discussed below.

The 5 liters stainless steel mixer had an electronic variable speed drive. The slowest speed was 62 rpm and the highest speed was 125 rpm.

- ✓ The second stage of mixing includes the introduction of other constituents while conserving flow time measurements and also following the protocol established by the AFREM method.

2.4 Experiments on SCC

The proportions of the different SCCs are shown in the Table 4. The RS is used in an initial water content of 15% to 20%. The choice of abandoning dried sediment for the formulation of concrete results from the last saturation dosages of the superplasticizer, the explanations are given below.

The total mixing time of SCC is 5 min. The Sediment preparation is always necessary to remove agglomerates. We use a 60-liter IGM concrete mixer at a constant speed, the mixing protocol is as follows:

- Introduce the RS and the amount of water required to reach the standard consistence (this water is removed from the total mixing water). Mix for 60s.
- Introduce the natural sand 0/4, mix for the 30s
- Introduce the gravel and mix for the 30s.
- Introduce 2/3 of the rest of the water, keep mixing for the 60s.
- Put the cement and diluted superplasticizer into 1/3 of the remaining water. Mix for the 4 min.

After mixing, the workability of fresh concrete is measured by the slump test using the Abrams cone according to EN 12350-2. For each mix F1C and F2C, nine cylindrical specimens (Ø110mm x H220 mm) (NF EN 12390-1) were cast to determine the compressive strength (NF EN 12390-3 standard). All SCC were cast without vibration and were treated in the laboratory at 20 ± 2 ° C for 24 h. There was no delay in setting time. After that, all the cylinders were made in 90 days.

2.5 Experiments on Paste

Sand with a grain size of less than 125 µm are dried in an oven at 105 ° C to a constant mass. 2 kg of RS is sieved at 125 µm by size distribution by wet sieving and maintained at a water content of 17%. Sand fines are obtained by size distribution at 125 µm according to NF EN

12948. All materials were covered in the laboratory at 20 ± 2 ° C for 24 h before the rheological tests.

- For SCC paste, sand and cement are mixed for 30 seconds. Then RS is introduced and the mixture mixed for 30s. Finally, we introduce the water and the superplasticizer and then the whole paste is homogenized by hand for 60 s. The total mixing time is 2 min. The mixture is left standing and the first measurements are taken 5 minutes after mixing (Fig. 5).
- For the other pastes indicated in the Table 6, they are turned for 2 min and allowed to stand for 5 minutes before the measured ones.

After mixing, a small amount of paste is used for each shear stress and viscosity measurement. The sample for the measurements is said to be homogeneous if the thickness of the paste is 5 times greater than the largest diameter of the grains D_{max}.

The slump of mortar was measured with Abrams' mini-cone. The yield stress as well as the plastic viscosities are measured for a ratio W / X = 0.46 and 0.48 (X = C, F, S_{ed}, C + S_{ed}, C + F). The names of the different pastes are shown in the Table 6.

2.6 Measurements procedures

2.6.1 Rheological measurements

The rheometer used is Anton Paar Modular Compact Rheometer MCR 102 equipped with a parallel plate geometry, the sample is put between two disks of the same symmetry axis and of same radius R = 12.5 mm, separated by a gap H = 1.25 mm. the shear rate $\dot{\gamma}(r)$ **(Eq.9)** depends only on the radius r. The velocity of a radius r is Ω r on the upper plate and zero on the lower plate, leading to Fig. 5.

$$\dot{\gamma}(r) = \frac{\Omega r}{H} \tag{9}$$

We can compute exactly shear stress τ(r) as:

$$\tau(r) = 2\frac{T}{\pi R^3}\frac{r}{R} \tag{10}$$

The measurement procedure is similar to the one used in L. Ducloué et al. [39]. The linear regression according to the Bingham model (Eq. 1) is done, the sample was then submitted to an increasing shear strain ramp from 0 s^{-1} to 0.1 s^{-1} during 30 s. The rheometer records the enhanced yield stress and plastic viscosity, as well as the structural build-up of the static yield

stress. When the structure broke down, the rheometer was stopped letting the paste rest for 15 min until the next stress growth (Fig. 5). This was continued until a total of 60 min.

Pre-shearing was carried out 5 minutes before the first yield stress measurement. The pre-shearing allowed for a homogeneous placement of the material in the parallel plates as well as a deflocculation of the fine particles.

2.6.2 SEM observation

SEM observations were made on fragments. The RS fragments are obtained by drying in an oven at 105 ° C and passed to the 125 µm sieve. The SCC paste fragments are curing for 7 days and then oven-dried at 40 ° C. The dimensions of the fragments are about 0.5 * 0.5 cm. They are polished and metallized with carbon to observe their microscopic structures. SEM images in Back-Scatter Detector (BSE) mode are shown in Figure 16 and Figure 17.

3 Results and discussion

3.1 Fresh properties of grouts

The saturation curves of the grouts are presented in Fig. 7. An analysis of the demand for superplasticizer (Sp *) as a percentage of dry extract of the cement weight allow us to deduce that:

$$(Sp^*)_{F1G} = 0.90 > (Sp^*)_{F2G} = 0.65 \quad (11)$$

From our table formulations, F1G and F2G it shows that:

$$(W/B)_{F1G} = 0.48 > (W/B)_{F1G} = 0.46 \quad (12)$$

$$(V_{sed} + V_c)_{F1G} = (V_{sed} + V_c)_{F2G} = 300\ l/m^3 \quad (13)$$

$$(V_s)_{F1G} > (V_s)_{F1G} \quad (14)$$

Where V_s the volume of sand is, V_{sed} is the volume of sediment and V_c is the volume of cement.

From (Eq. 11)(Eq. 12)(Eq. 13)(Eq. 14), F1G should require less superplasticizer because it contains more water and more fine sand. To better understand, we calculated the saturation dose of RS ($Sp^*{}_A$). The saturation dose of cement CEM III / A 42.5 in alone ($Sp^*{}_C$) is 0.38% in dry extract of the weight of the cement which makes it possible to deduce:

$$Sp^*_A = \left(100\ x\ Sp^*_{C+A} - (100 - A\%)\ x\ Sp^*_C\right)/A\% \quad (15)$$

Where A% is the percentage of sediment in each Table 5 of the grout. It is deduced that Sp^*_A is 2.55% and 1.55% respectively for F1G and F2G. The results of saturation doses of the grouts are confirmed. The mass percentage of sediment in F1G is higher than that of F2G, which justifies the higher need for superplasticizer.

The paste volume of each grout is greater than 15%, the optimization of 80% saturation dosage (Sp^*) is indicated. It says that:

$$\frac{Sp}{Sp*} = 0.80 \quad (16)$$

The values of Sp are indicated in the Table 4and used to characterize the rheological properties. The slump value of F1G and F2G shrinks little by little over time. An addition of RS brings about a slower increase in structural viscosity of grout in time Fig. 7. Despite the elongated mixing time to remove agglomerates, we observe the presence of agglomerates for formulations whose RS has been dried at 105 ° C. The slump value of these nuts diminishes because of the agglomerates.

3.2 Properties of SCC

The fresh density of concrete was 2378, 2371kg/m3 for F1C, F2C respectively. The workability of the concrete was assessed by measurements of slump flow. The flow of SCC in an unconfined area is characterized by the Abrams cone flow. They were 690, 680 mm for F1C and F2C respectively Fig. 9. [12]. There was no segregation or bleeding. We can deduce that an increase in the amount of sediment implies an increase in the dosage of the water and the superplasticizer. The fine particles of RS were limited to the bleeding phenomenon. Fig.10. present the compressive strengths of SCC (average values obtained by three measurements for compressive strength). Compressive strengths of F1C and F2C after 90 days increased. At 28 days they were 21, 25 MPa for F1C, F2C respectively. At 90 days, there was an increase in resistance of 10 to 15%. F1C and F2C respect the specifications for the construction of nonstructural works.

3.3 Fresh properties of paste

3.3.1 Yield stress variation and Viscosity Measurements

The structural build-up for RS paste, cement paste, filler paste for paste symbols WS_{ed}, WC, WF respectively was illustrated in Fig. 11. The yield stress of WS_{ed} is higher than that of WC

and also the paste WF. The WCS_{ed} and WCF paste allows us to analyze the rheological behavior of the cement / RS complex Fig. 12.

It follows that the volume replacement at a rate t = 28% of a portion of the cement WC paste by sediment causes an increase in the yield stress figure. These results also explain the need for water and high superplasticiser for F1C grout and SSC F1C. However the opposite phenomenon is observed for the filler. Because when the volume is replaced at the same rate a portion of the cement of the paste WC. In the filler, there is a decrease in the yield stress (Fig. 11). L. Rudzinski in his thesis explains that the introduction of mineral additions brings a reduction in fluidity. By substituting the volume of a portion of the cement/sediment complex with sand fines, without increasing the amount of water, the $WCS_{ed}S$ paste is obtained. It is found that the presence of fine sand allows the reduction of the yield stress (Fig. 13).The resulting F1P and F2P paste of SCC F1C and F2C respectively, have lower yield stress compared to the rest. The introduction of the superplasticizer decreases the yield stress and facilitates the slumping of the pastes (Fig. 12)

Plastic viscosities presented in the figure are measured after 45 min of formulation. Fig. 14. shows that the presence of the sediment makes the paste more viscous. One can observe a non-linear, approximating exponential increase in F1P and F2P viscosity. The provision of a viscosity agent was not required for sediment-based formulated concrete.

3.3.2 Slump Measurements

After 45 minutes of mixing, the mini-slump flow value of the F1P and F2P paste were 91.63 and 79.17 cm respectively. The theoretical slumps are calculated using yield stress data collected by the rheometer. According to Coussot and Roussel, the yield stress is linked to slump by the following formula [40]:

$$\tau_0 = \frac{225\rho g \Omega^2}{128\pi^2 R^5} \quad \textbf{(17)}$$

The theory slump value of the F1P and F2P paste were 86.77 and 80.98 respectively. Fig.15. shows the parts of the different slump. The comparison of the experimental results with the theoretical results supports the validity of the theological program of the study.
Furthermore, the maintenance of workability is explained by the presence of the clay fraction in the SR. The illites present in the sediment can bind the calcium ions released by the cement and thus help to reduce hydrate formation. The modification of the hydration kinetics of the cement causes a delay in the setting time of the cement and a maintenance of the viscosity.

3.4 Microstructural properties of Paste

The OM content of 3.33% comes mainly from the calcination in the oven at 450 ° C from plant debris. The BSE SEM (Fig.16. and Fig.17.) of the RS shows the presence of microparticles of elongated shapes. This is the vegetable organic matter as discussed by K. H. Moa et al. , the rheology of cement-based materials is dependent on many parameters including the presence of fibers [41]. The presence of fiber oriented in all directions increases the shear strength [41].

In the same way, the organic matter consists mainly of humus, divided into fulvic acids and humic acids. This phase of organic matter represents 80 to 90% of the total organic carbon (TOC) of RS. The presence of these acids disturbs the hydration of the cement and leads to a modification of the rheological behavior of SCC in the fresh state.

In addition, we observe shell remains in the RS, their porous structures and irregular shapes influence the water demand in the RS (Fig. 16) These elements are present in the F1P and F2P pastes. After hydration of the cement, it is observed that a thin layer of cement paste covers some irregular shapes of the shell (Fig. 17) This probably explains the decrease of the yield stress during the introduction of the cement in the WS paste [42].

4 Research significance and recommendation for the use of fine sediments in SCC

The problem of sediment incorporation in self-compacting cementitious materials lies mainly in their very heterogeneous characteristics, particularly the presence of organic matter, clays and shells. The classical approach to the use of sediments in self-compacting concrete consists of partially replacing cement fraction with calcined and crushed sediments. The present study proposes an innovative approach that consists of partially substituting part of the sand with raw sediment from active lagoons. Through the results of this study, several recommendations can be made. It is suggested to:

- Conduct an environmental assessment of the RS before use. Indeed, the presence of organic matter and heavy metals (lead, copper, arsenic, etc.) can considerably affect the chemical properties and durability of concrete. Depending on the concentration of pollutants, it is advisable to use raw sediment classified as inert or non-hazardous material following the European directive 12/12/14/EC.
- Quantify the fine fraction of the RS. A percentage between 25 and 40% of fine particles below 125 µm is preferable. The results of the rheological properties have

shown that the presence of fine sediment particles leads to an increase in viscosity and a decrease in workability of the concrete. The rheological behavior of SCC depends strongly on the values of the shear stress. For an identical rheometer setting according to our study, it is recommended to have the following SCC paste shear stress values:

  - Between 20 and 25 Pa at 15 minutes after mixing for a W/B ratio = 0.46
  - Between 15 and 20 Pa at 15 minutes after mixing for a W/B ratio = 0.48

- To determine the physical, chemical and mineralogical properties of the fine fraction of sediments. Knowledge of the water demand of the fine fraction as well as the type of clay present in the RS fines, allows the optimization of the formulation parameters, in particular the W/B ratio.

- Use less than 20% of raw sediment in the formulation of self-compacting concrete. This avoids the negative effects of sediment on the mechanical properties of the concrete and also allows optimization of the dosage of additives.

- Do not use viscosity enhancers for the formulation of self-compacting concrete based on RS from active lagoons. The hydrophobic nature of the clay in the sediment increases the stability of the concrete and improves its ability to resist the shear stresses induced by its weight.

5 Conclusion

To meet the ecological and raw material depletion objectives, we proposed and experimented with two formulations of SCC. These formulations include about 300 kg /m^3 of raw sediment. The purpose of this article is first to study the experimental feasibility of SCC without mineral addition but incorporating a high amount of raw sediment, then to analyze the impact of sediments on the rheological properties of SCC pastes. The relevant conclusions that emerge were:

- Non-hazardous sediment with an initial water content of 15 to 20% can be used at a high level to formulate SCC. The presence of the sediment ensures the good stability of the SCC. There is no segregation or bleeding in the fresh state. The 28-day compressive strengths confirm the use of RS-based concrete for nonstructural works. At the economic and ecological level, this result is particularly important because they are used in large quantities and require no physical and thermal treatment.

- The presence of RS increases the yield stress of SCC, there is a decrease in the mobility of SCC in an unconfined environment. RS fines do not have the same rheological behavior as other limestone mineral additions. The F1 fraction of the RS influences the water demand and superplasticizer of SCC. OM in SCC from sediment is also a major factor influencing the rheology of concrete.
- The dried state of the RS is not indicated for the formulation of SCC because after mixing, agglomerates can be observed which reduce the rheological and mechanical properties.

The densified mixture design algorithm (DMDA) based on the least void condition through the utilization of RS to fill the void between blended aggregates and cement paste to fill the rest of the void was used. To evaluate the influence of RS of the mix, a rheological study of comparison of yield stress accomplished made it possible to detect influential the parameters of the intrinsic properties of the raw sediment. The analysis of the results highlighted the real relevance of the OM and a fine fraction of RS, on the rheological properties of SCC formulated.

Extensive research is going on in our laboratories to increase the mechanical properties and durability of SCC based on raw sediment.

Ethical Approval

'Not applicable'

Consent to Participate

'Not applicable'

Consent to Publish

'Not applicable'

Authors Contributions

' Nongwendé Philippe OUEDRAOGO: Conceptualisation, Data curation, Formal analysis, Methodology, Validation, Writing - original draught, Writing - review & editing. Frédéric Becquart: Validation, Resources, Supervision, Funding acquisition, Writing - review & editing. Mahfoud Benzzerzour: Validation, Resources, Supervision, Funding acquisition. Nor-Edine. ABRIAK: Validation, Resources, Project administration's

Funding

'Not applicable'

Competing Interests

'The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.'

Availability of data and materials

'The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request'.

Acknowledgements

Authors would like to acknowledge the IMT Lille Douai for research funds.

References

[1] H. Okamura, K. Ozawa, and M. Ouchi, "Self-compacting concrete," *Struct. Concr.*, vol. 1, no. 1, pp. 3–17, 2000.

[2] C. Shi, Z. Wu, K. Lv, and L. Wu, "A review on mixture design methods for self-compacting concrete," *Constr. Build. Mater.*, vol. 84, pp. 387–398, 2015.

[3] J. M. D'ALOIA SCHWARTZENTRUBER, Laetitia and Torrenti, *Le grand livre des bétons*. ÉDITIONS LE MONITEUR, 2014.

[4] C. L. G. P. Raujouan, "Enquête Dragage 2010 - Synthèse des données, Centre d′Études Techniques Maritimes Et Fluviales (CETMEF)," 2013.

[5] V. Dubois, N. E. Abriak, R. Zentar, and G. Ballivy, "The use of marine sediments as a pavement base material," *Waste Manag.*, vol. 29, no. 2, pp. 774–82, Feb. 2009.

[6] H. Van Damme, "Cement and Concrete Research Concrete material science : Past , present , and future innovations ☆," *Cem. Concr. Res.*, vol. 112, no. May, pp. 5–24, 2018.

[7] P. de C. Predis Calais and G. de travail N°5, "Améliorer la valorisation des déchets industriels en BTP," 2006.

[8] I. Ennahal, W. Maherzi, Y. Mamindy, P. Mahfoud, B. Nor, and E. Abriak, "Eco-friendly polymers mortar for floor covering based on dredged sediments of the north of France," *J. Mater. Cycles Waste Manag.*, vol. 0, no. 0, p. 0, 2019.

[9] R. Achour, "Valorisation et caractérisation de la durabilité d 'un matériau routier et d 'un béton à base de sédiments de dragage," *Thèse Dr. Univ. Lille*, p. 199, 2013.

[10] F. K. Aoual, D. Kerdal, M. Ameur, B. Mekerta, and A. Semcha, "Durability of mortars made with dredged sediments," vol. 118, pp. 240–250, 2015.

[11] E. Canada, A. Gosselin, D. Blackburn, and M. Bergeron, "*Protocole d ' évaluation de la traitabilité des sédiments , des sols et des boues à l'aide des technologies minéralogiques*". 1999.

[12] A. P. N. B. P, "Groupe de travail 'Recommandations pour l'emploi des Bétons Auto-Plaçants,'" 2008.

[13] D. E. S. Ponts, E. T. Chaussees, and J. Chappuis, "These T. Sedran," 1999.

[14] K. Ouhba, L. Benamara, A. H. Hamoui, A. Hamwi, and M. D. Loye, “Conception of a synthesis pozzolan from sediment dams calcined (Case : Gargar dams),” vol. 3, 2014.

[15] M. Benzerzour, M. Amar, and N. Abriak, “New experimental approach of the reuse of dredged sediments in a cement matrix by physical and heat treatment,” *Constr. Build. Mater.*, vol. 140, pp. 432–444, 2017.

[16] T. A. Dang, S. Kamali-Bernard, and W. A. Prince, “Design of new blended cement based on marine dredged sediment,” *Constr. Build. Mater.*, vol. 41, pp. 602–611, Apr. 2013.

[17] Z. Zhao, M. Benzerzour, N. Abriak, D. Damidot, L. Courard, and D. Wang, “Use of uncontaminated marine sediments in mortar and concrete by partial substitution of cement,” *Cem. Concr. Compos.*, vol. 93, no. July, pp. 155–162, 2018.

[18] T. A. Dang, S. Kamali-Bernard, and W. A. Prince, “Design of new blended cement based on marine dredged sediment,” *Constr. Build. Mater.*, vol. 41, pp. 602–611, Apr. 2013.

[19] M. Amar, M. Benzerzour, N. Abriak, and Y. Mamindy-pajany, “Study of the pozzolanic activity of a dredged sediment from Dunkirk harbour,” *Powder Technol.*, vol. 320, pp. 748–764, 2017.

[20] M. Amar, “Towards the establishment of formulation laws for sediment-based mortars,” *J. Build. Eng.*, vol. 16, no. August 2017, pp. 106–117, 2018.

[21] E. Rozière, M. Samara, A. Loukili, and D. Damidot, “Valorisation of sediments in self-consolidating concrete: Mix-design and microstructure,” *Constr. Build. Mater.*, vol. 81, pp. 1–10, Apr. 2015.

[22] Z. Lafhaj *et al.*, “The use of the Novosol process for the treatment of polluted marine sediment,” vol. 148, pp. 606–612, 2007.

[23] Z. Lafhaj, M. Samara, F. Agostini, L. Boucard, F. Skoczylas, and G. Depelsenaire, “Polluted river sediments from the North region of France: Treatment with Novosol® process and valorization in clay bricks,” *Constr. Build. Mater.*, vol. 22, no. 5, pp. 755–762, May 2008.

[24] Franck Agostini, Thèse de doctorat Ecole Centrale De Lille, “Inertage et valorisation des sédiments de dragage marins,” 2007.

[25] Z. Lafhaj, Z. Duan, I. Bel Hadj Ali, and G. Depelsenaire, “Valorization of treated river sediments in self compacting materials,” *Waste and Biomass Valorization*, vol. 3, no. 2, pp. 239–247, 2012.

[26] R. Snellings *et al.*, “Properties and pozzolanic reactivity of flash calcined dredging sediments,” *Appl. Clay Sci.*, vol. 129, pp. 35–39, Aug. 2016.

[27] J. Ramaroson, “Calcination des sédiments de dragage contaminés. Etudes des propriétés physico-chimiques,” p. 181, 2008.

[28] J. Couvidat, M. Benzaazoua, V. Chatain, and H. Bouzahzah, “Environmental evaluation of dredged sediment submitted to a solidification stabilization process using hydraulic binders,” *Environ. Sci. Pollut. Res.*, vol. 23, no. 17, pp. 17142–17157, 2016.

[29] J. Couvidat, M. Benzaazoua, V. Chatain, A. Bouamrane, and H. Bouzahzah, "Feasibility of the reuse of total and processed contaminated marine sediments as fine aggregates in cemented mortars," *Constr. Build. Mater.*, vol. 112, pp. 892–902, Jun. 2016.

[30] P. Ozer-Erdogan, H. M. Basar, I. Erden, and L. Tolun, "Beneficial use of marine dredged materials as a fine aggregate in ready-mixed concrete: Turkey example," *Constr. Build. Mater.*, vol. 124, pp. 690–704, 2016.

[31] L. Ben Allal, M. Ammari, I. Frar, A. Azmani, P. Clastres, and S. Jullien, "Stabilization of contaminated canal sediments," *Eur. J. Environ. Civ. Eng.*, vol. 15, no. 2, pp. 293–302, 2011.

[32] W. P. Limited, *Understanding the rheology of concrete*. .

[33] D. W. Pribyl, "Geoderma A critical review of the conventional SOC to SOM conversion factor," *Geoderma*, vol. 156, no. 3–4, pp. 75–83, 2010.

[34] A. Perrot, T. Lecompte, H. Kheli, C. Brumaud, J. Hot, and N. Roussel, "Cement and Concrete Research Yield stress and bleeding of fresh cement pastes," vol. 42, pp. 937–944, 2012.

[35] P. Chang, C. Hwang, and Y. Peng, "Application of High-Performance Concrete to High-Rise Building in Taiwan," vol. 4, no. 2, pp. 65–73, 2001.

[36] C. L. Hwang, M. F. Hung, and Y. Y. Chen, "Comparison of ACI Mixture Design Algorithm to HPC Desified Mixture Design Algorithm in the Anti-corrosion and Durability Design," *J. Chinese Corros. Eng.*, vol. 16, no. 4, pp. 281–296, 2002.

[37] Y. Chen, B. Le, A. Tuan, and C. Hwang, "Effect of paste amount on the properties of self-consolidating concrete containing fly ash and slag," *Constr. Build. Mater.*, vol. 47, pp. 340–346, 2013.

[38] F. De Larrard, F. Bosc, C. Catherine, and F. Deflorenne, "The AFREM method for the mix design of high performance concrete," vol. 30, no. September, pp. 439–446, 1997.

[39] L. Ducloué *et al.*, "Yielding and flow of foamed metakaolin pastes To cite this version : HAL Id : hal-01205614 Yielding and flow of foamed metakaolin pastes," 2015.

[40] N. Roussel, C. Stefani, and R. Leroy, "From mini-cone test to Abrams cone test : measurement of cement-based materials yield stress using slump tests," vol. 35, pp. 817–822, 2005.

[41] K. Hung, U. J. Alengaram, M. Zamin, S. Cheng, W. Inn, and C. Wah, "Recycling of seashell waste in concrete : A review," *Constr. Build. Mater.*, vol. 162, pp. 751–764, 2018.

[42] C. Martínez-garcía, B. González-fonteboa, F. Martínez-abella, and D. C.- López, "Virtual Special Issue Bio Based Building Materials Performance of mussel shell as aggregate in plain concrete," vol. 139, pp. 570–583, 2017.

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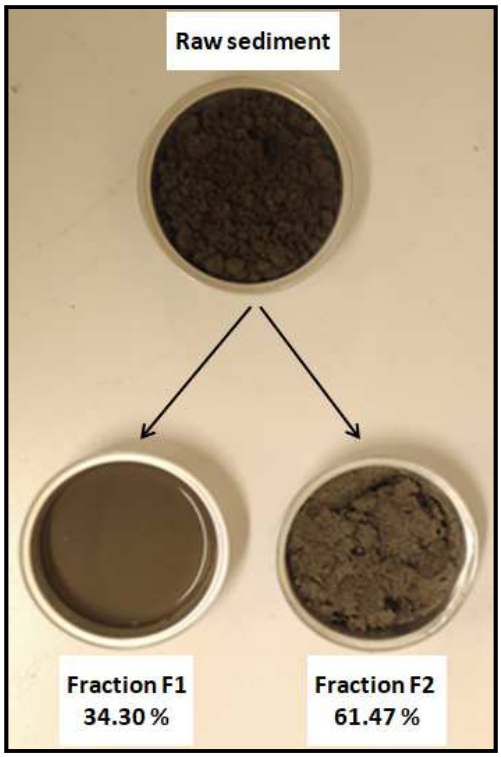

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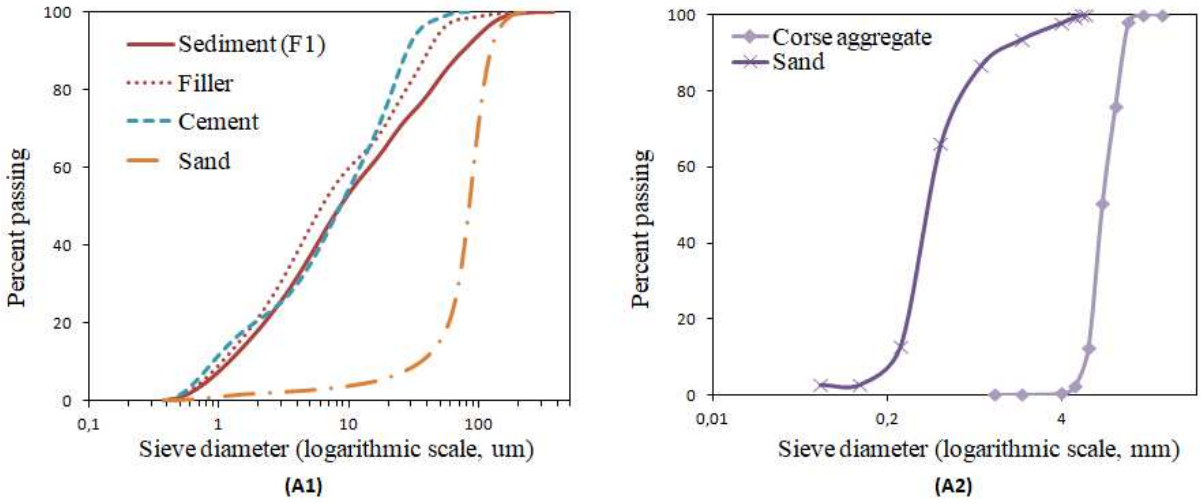

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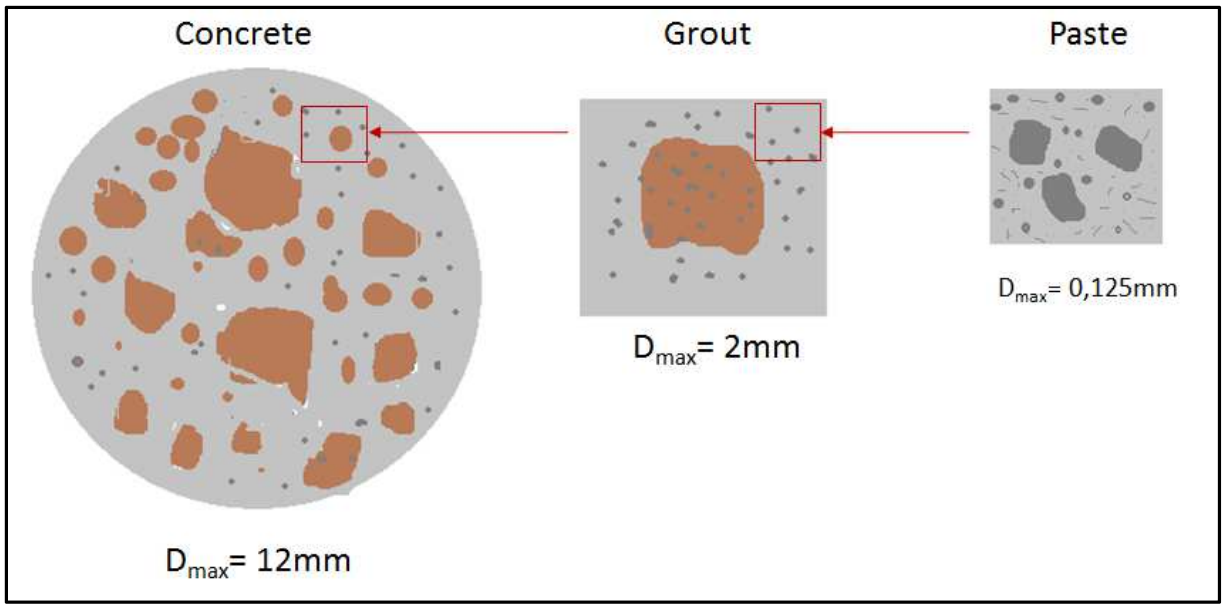

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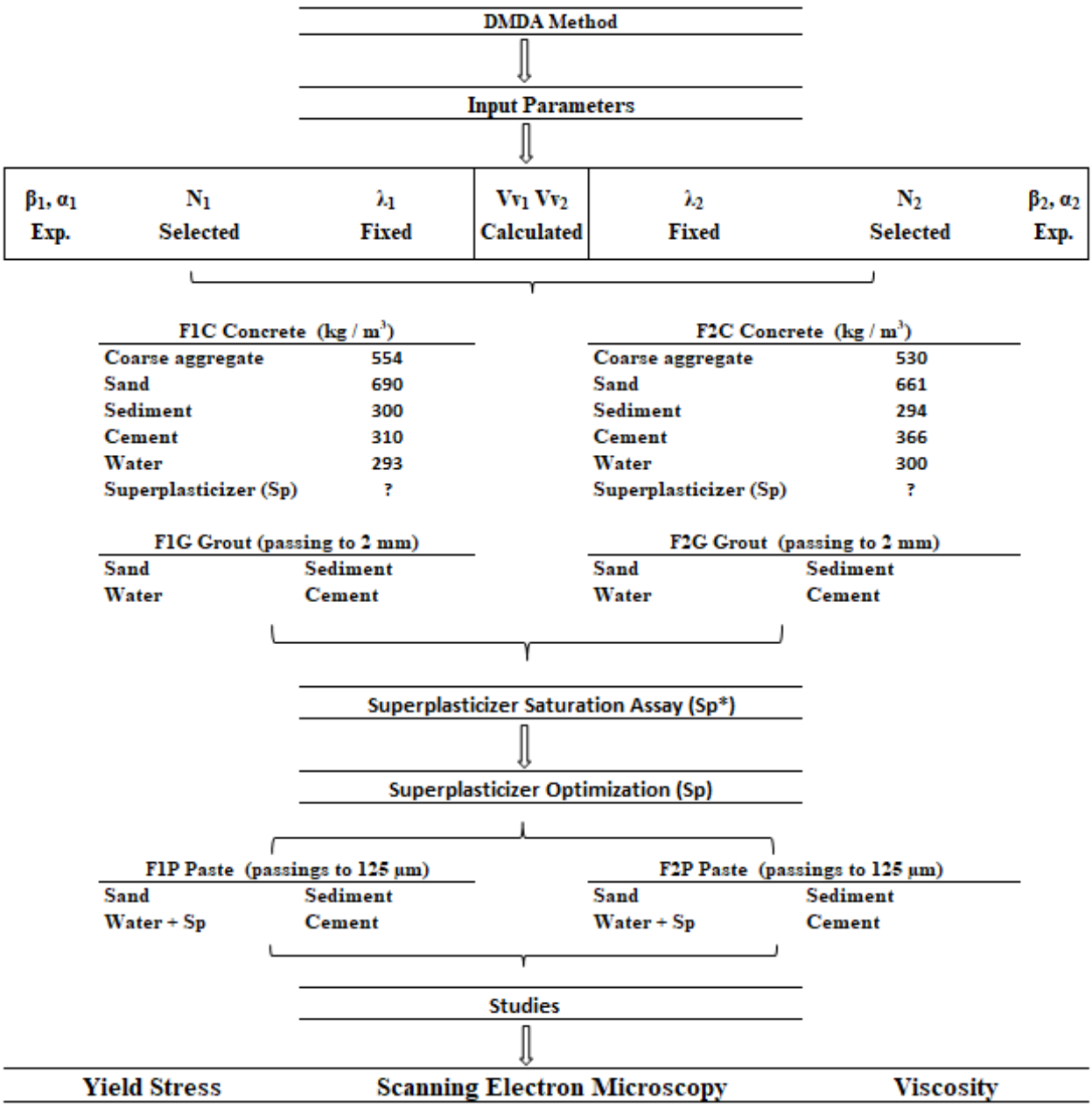

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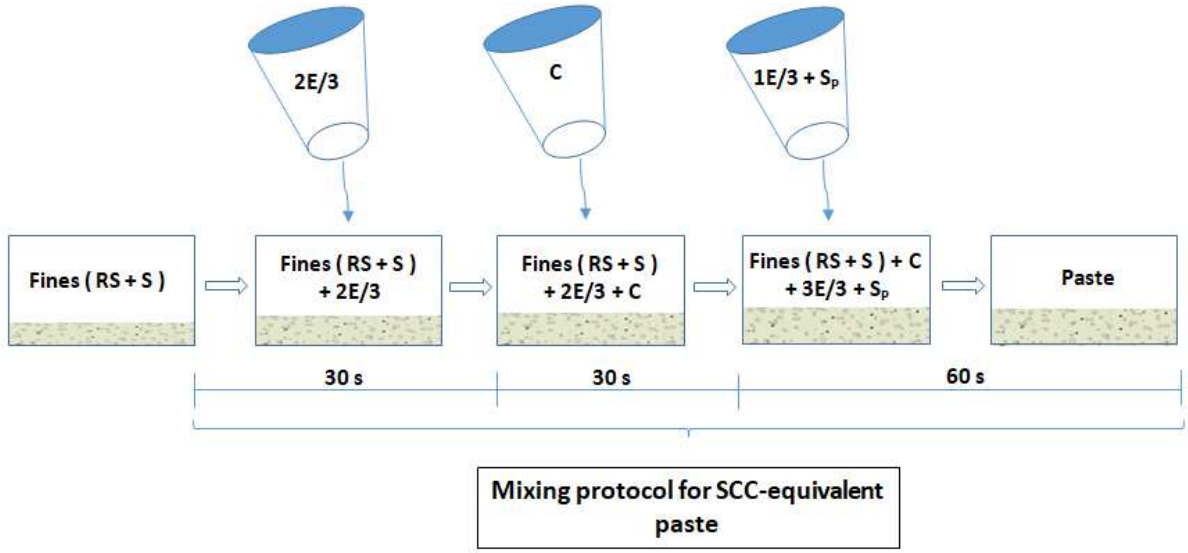

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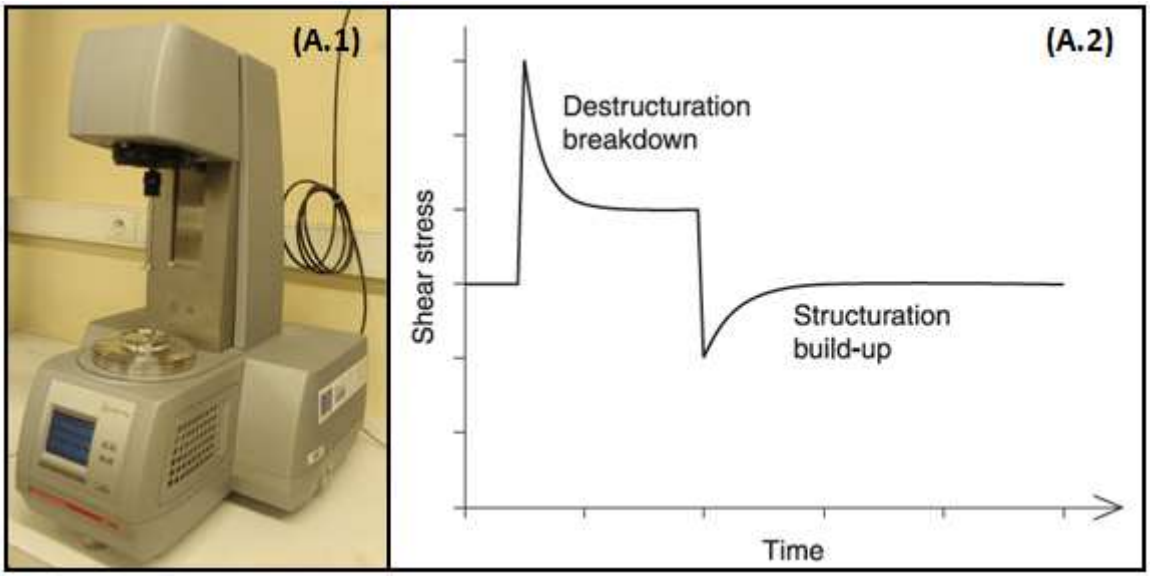

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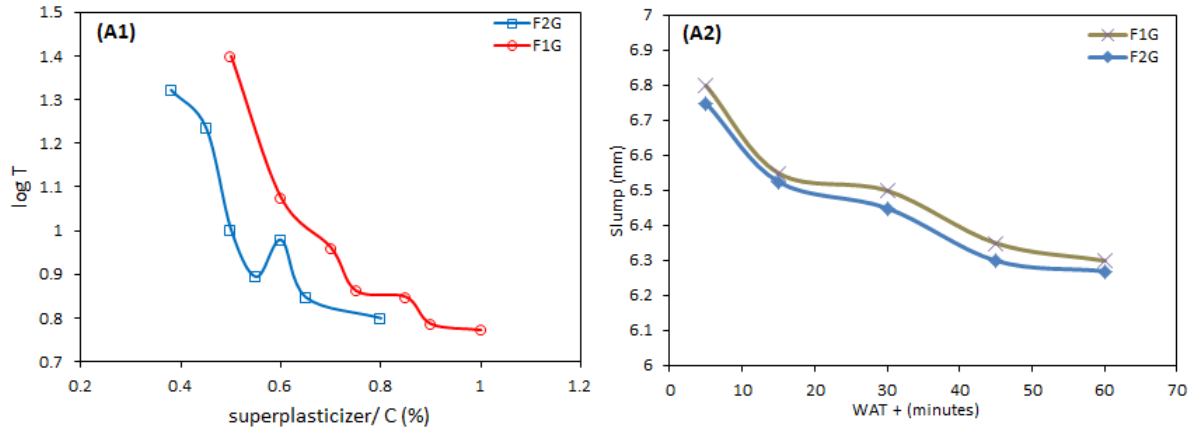

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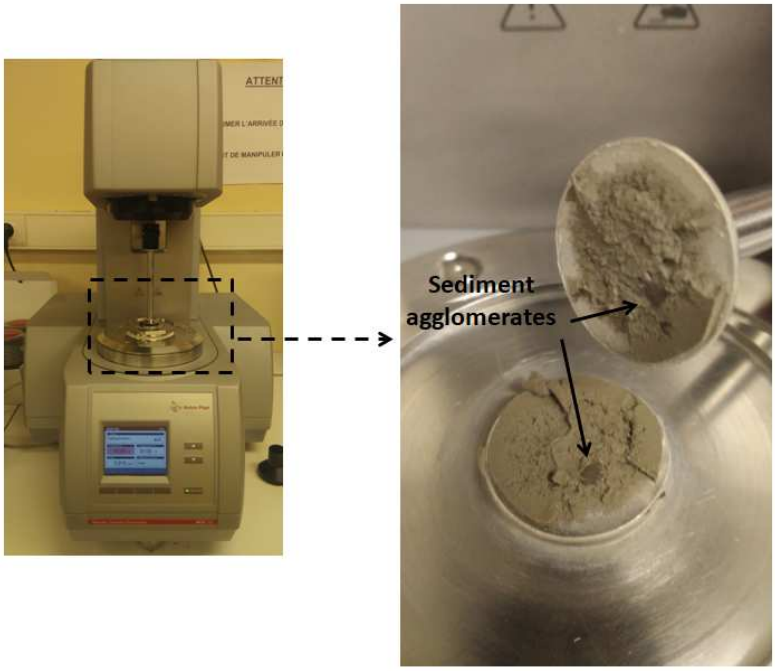

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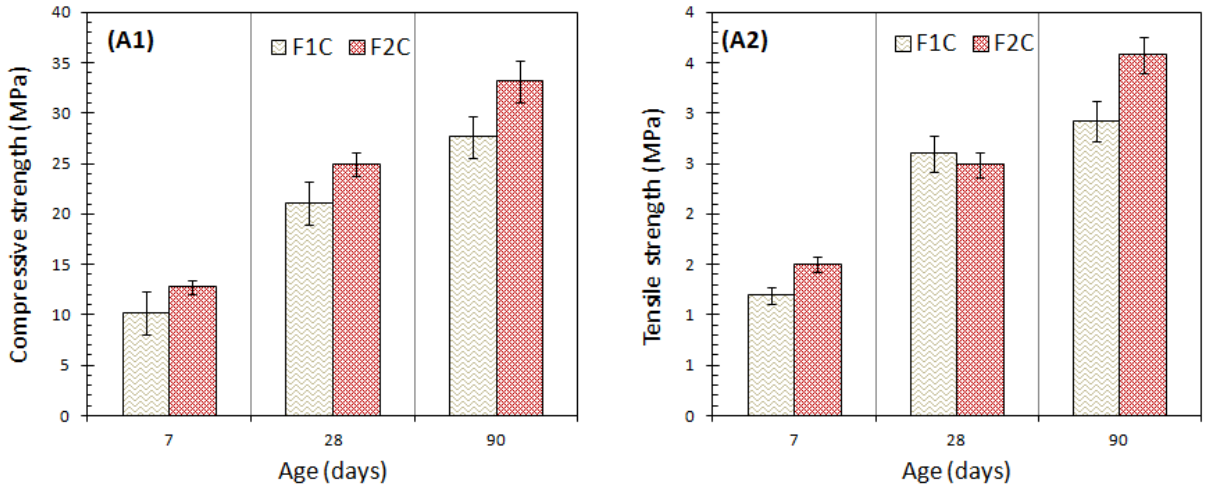

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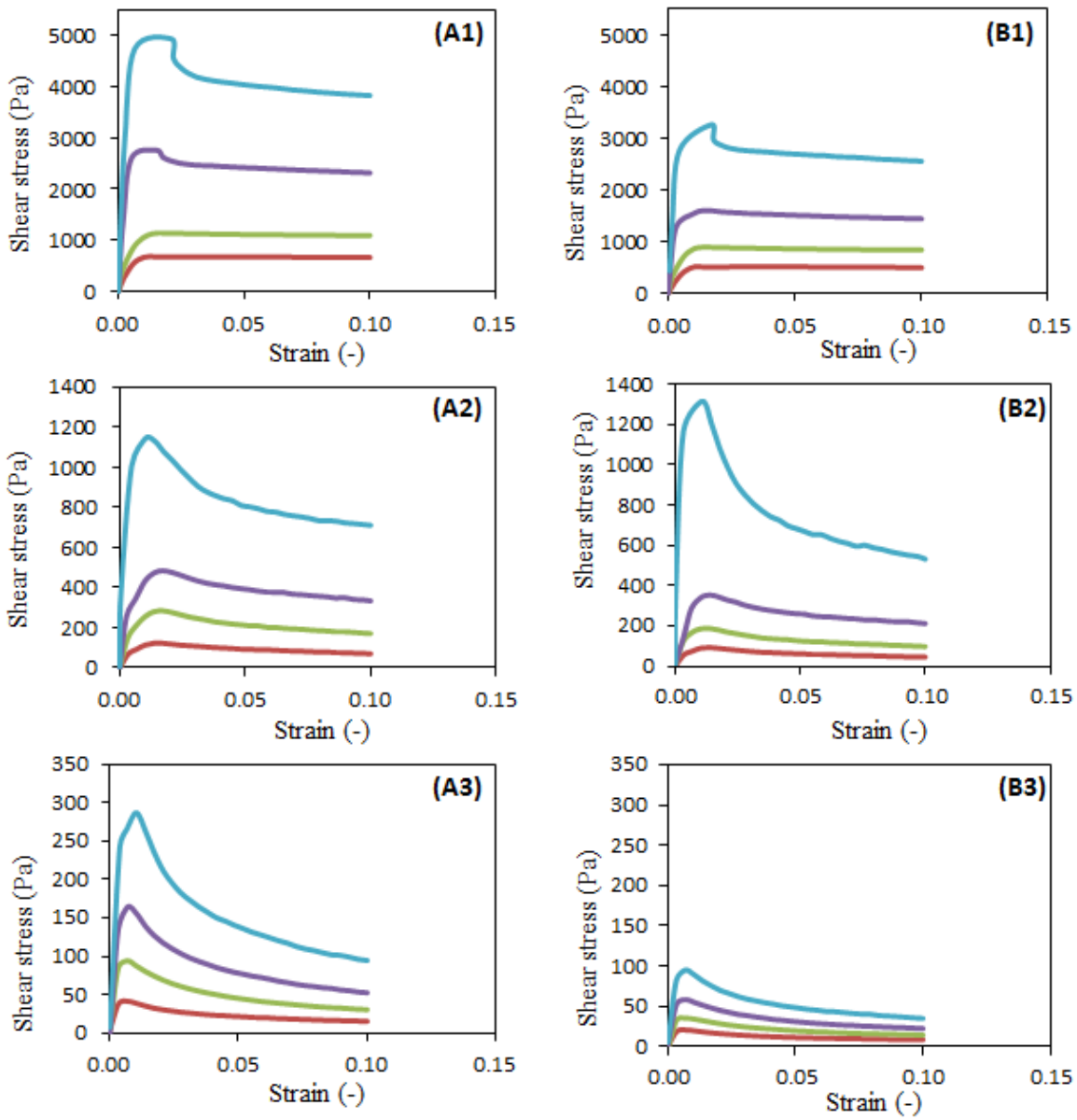

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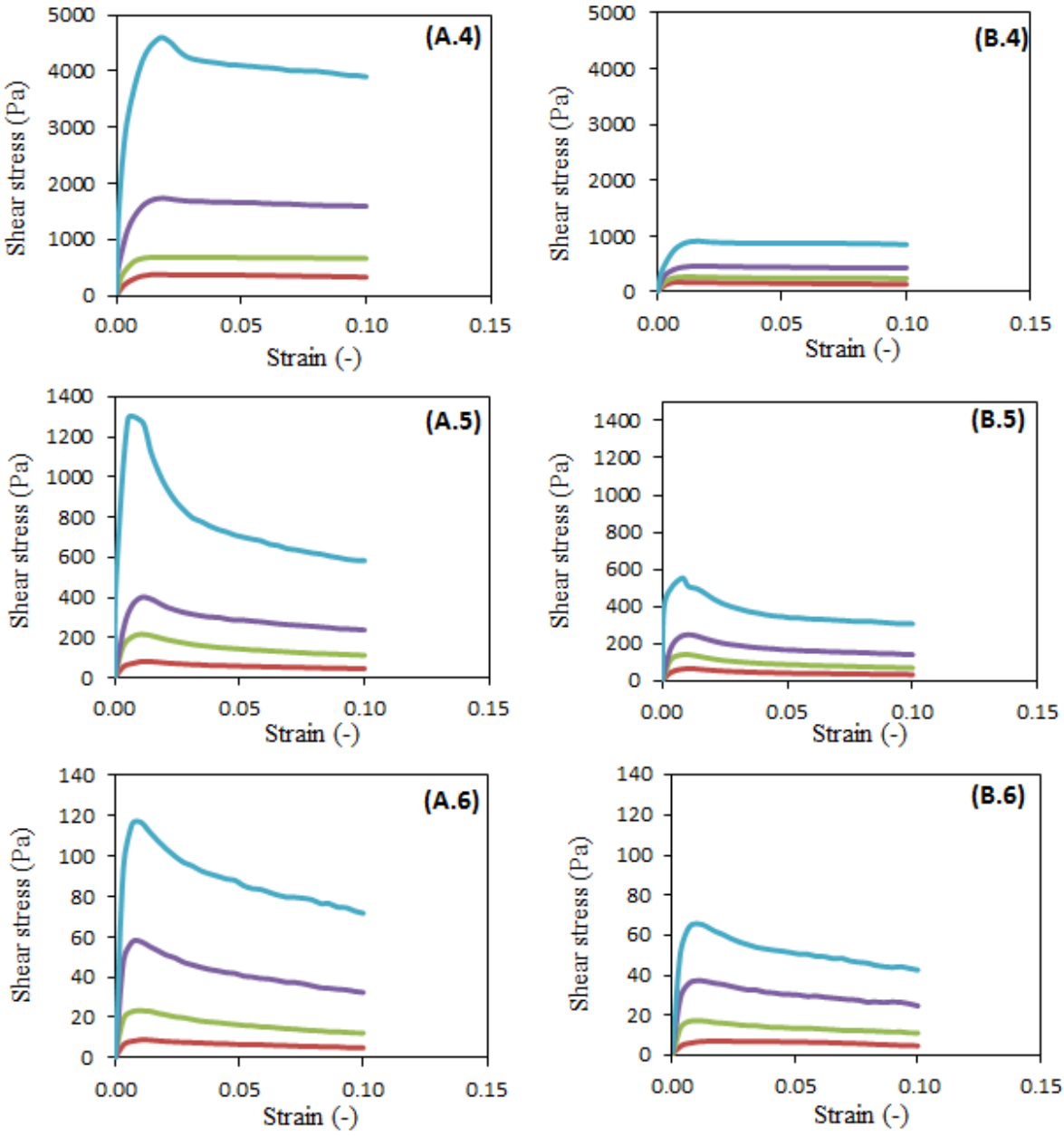

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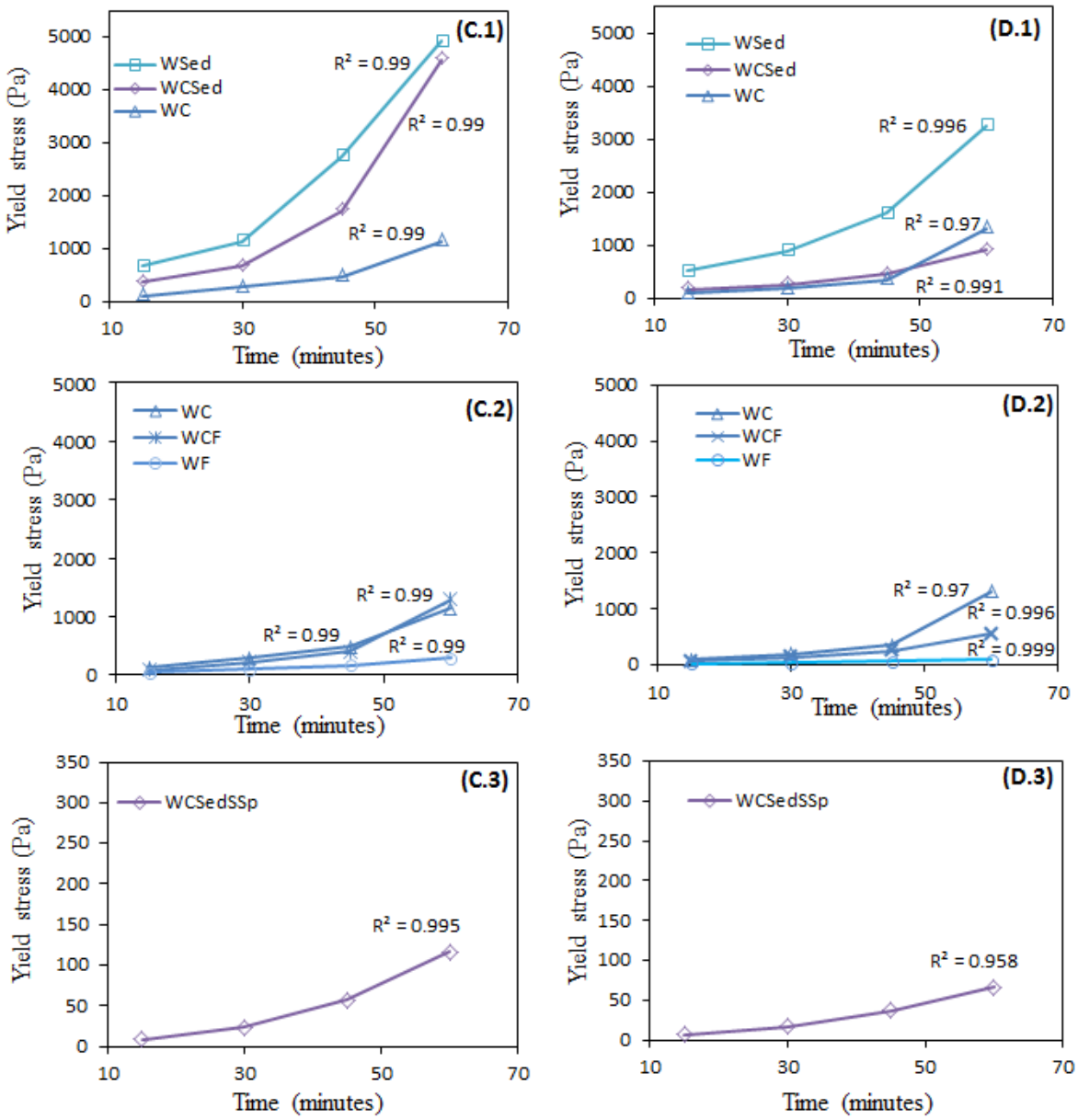

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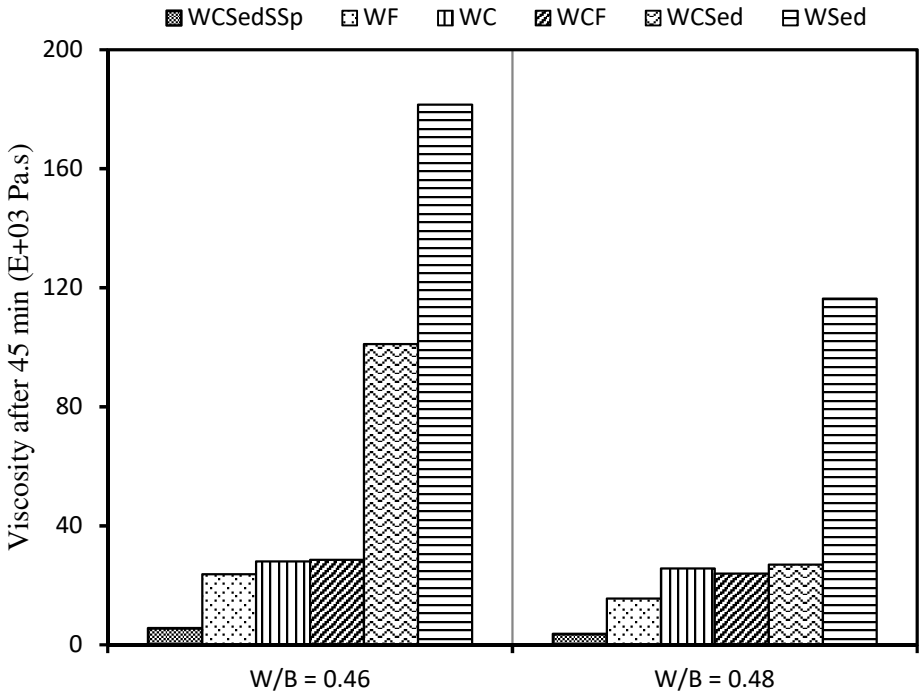

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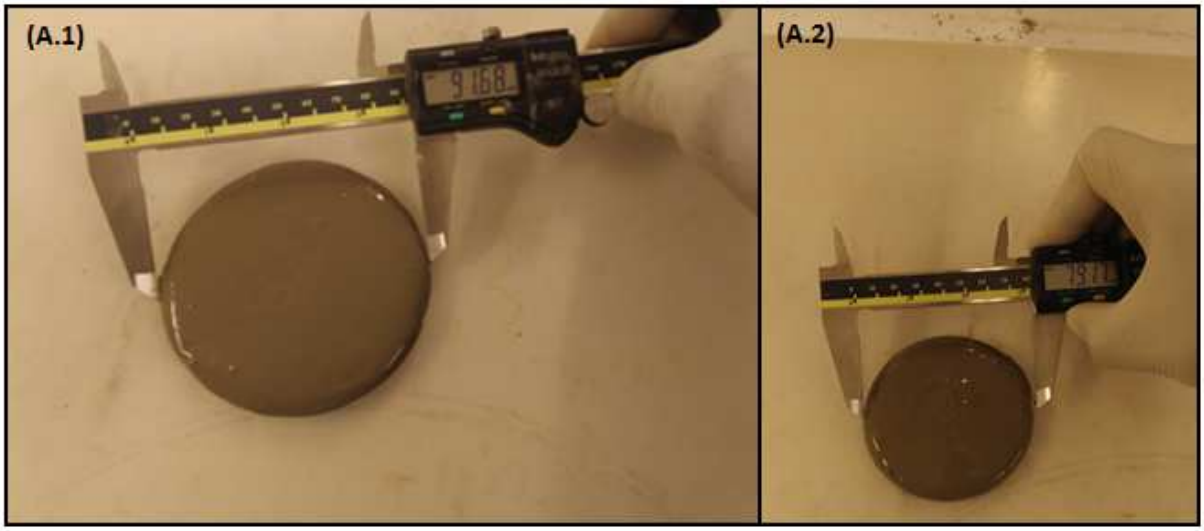

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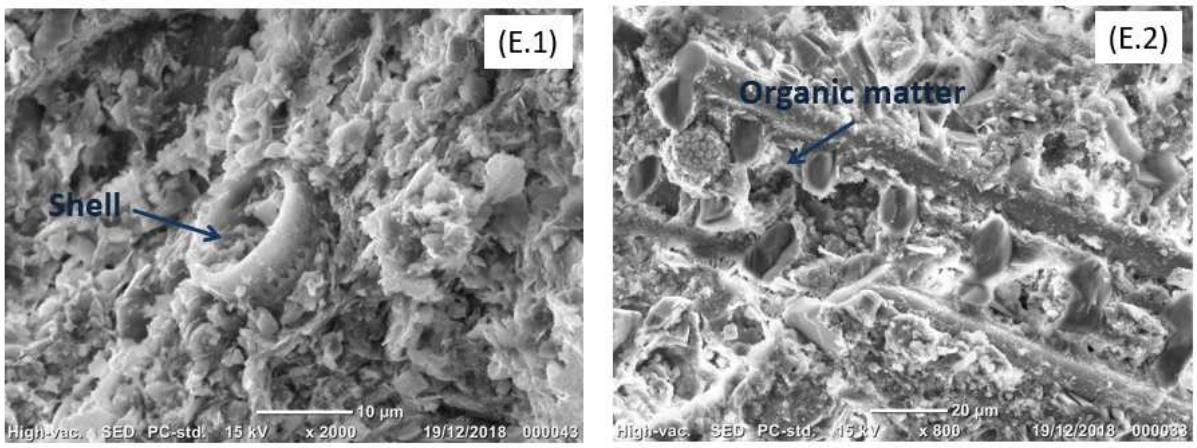

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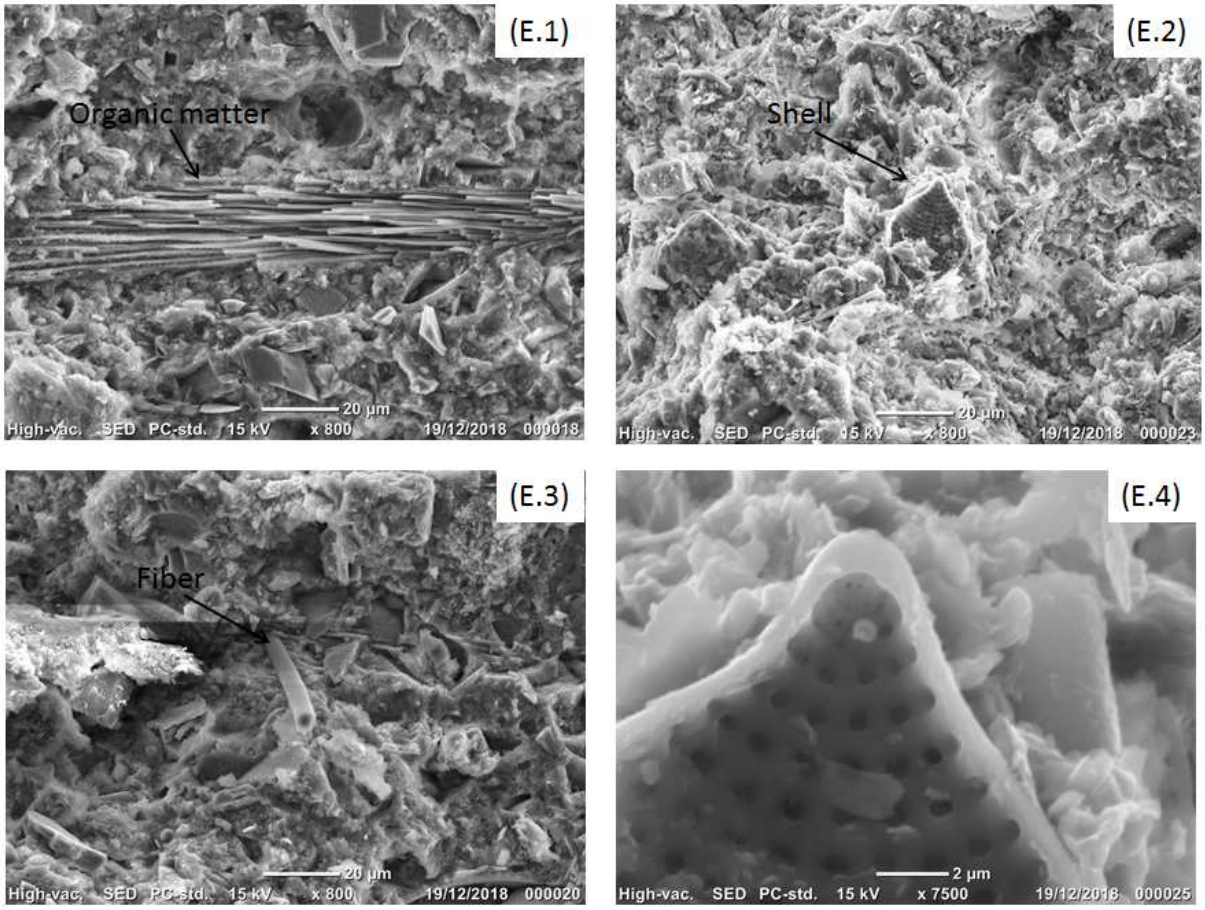

Fig. 17. SEM micrographs of SCC paste

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Table 7. Physical properties of coarse aggregates and sand

Physical properties	Natural aggregates	
	Corse (4/11.2 mm)	Sand (0/4 mm)
Specific gravity	2.45	2.64
Bulk density (kg/m3)	1456	1718
Micro-Deval test (%)	11	/
Los Angeles abrasion test(%)	21	/
Fineness modulus	/	2.72
Absorption capacity (%)	0.43	1.1

Table 8. Oxide composition of cement and raw sediments using XRF (%)

Oxides composition	Materials	
	Raw sediments	CEM III 42.5 N
SiO_2	56.39	26.1
Al_2O_3	4.70	7.8
MgO	0.91	3.4
Fe_2O_3	1.95	2.2
CaO	12.75	55
Na_2O	1.22	0.32
K_2O	1.16	-
P_2O_5	0.20	-
SO_3	0.90	2.03
TiO_2	0.19	-
MnO	Trace	-
ZnO	Trace	-

Table 9. Leaching test results and limiting values of classification of wastes from 28 October 2010/CE

Heavy metals mg/kg dry mass	Raw sediment	Inert	Non-Dangerous	Dangerous
Barium	27.47	20	100	300
Chromium	0.17	0.5	10	70
Copper	4.69	2	50	100
Nickel	0.23	0.4	10	40
Lead	0.13	0.5	10	50
Zinc	0.55	4	50	200
Cadmium	0.035	0.04	1	5
Molybdenum	2.71	0.5	10	30
Arsenic	0.51	0.5	2	25

Mercury	<0.0010	0.01	0.2	2

Table 10. Mix proportioning of concrete, grout and paste

materials of SCC mixtures 1 m³	**Mixture label**					
	F1C	F1G	F1P	F2C	F2G	F2P
Cement CEM III / A (kg)	310	396	838	366	460	933
Coarse aggregate (kg)	554	-	-	530	-	-
Sand (kg)	690	824	43	661	778	48
Sediment (kg)	300	383	318	294	371	289
Water (kg)	293	374	556	300	378	562
Efficient water (kg)	236	301	449	246	309	456
Superplasticizer (kg)	11	14	30	10	12	24
W/C	0.94	0.94	0.66	0.82	0.82	0.60
W_{eff}/C	0.76	0.76	0.53	0.67	0.67	0.48
W/B = W/(C + S_{ed})	0.48	0.48	0.48	0.46	0.46	0.46
$W_{eff}/(C + S_{ed})$	0.39	0.39	0.39	0.37	0.37	0.37
S_p/C (%) dry extract of cement mass	0.72	0.72	0.72	0.52	0.52	0.52
N	1.164	1.164	1.164	1.190	1.190	1.189
Total fine content < 125 µm (%)	24	35	100	27	39	100
Sediment fines content < 125 µm (%)	6	9	100	6	9	100

Table 11. Mix percentage of coarse aggregates, sand, sediment, and cement in the dry granular matrix

Percentages of the various components determined by DMDA.	**Mixture label**					
	F1C	F1G	F1P	F2C	F2G	F2P
Cement	17	25	69.9	20	29	73.5
Sediment	16	24	26.6	16	23	22.8
Coarse aggregate	30	0	0.0	29	0	0.0
Sand	37	51	3.6	36	48	3.7

Table 12. Paste nomenclature for W/B = 0.46 and W/B = 0.48

Nomenclature		**Paste Symbols**
W/C	Water/Cement	WC
W/S_{ed}	Water/Sediment	WS_{ed}
W/F	Water/ Filler	WF
W/B = W/(C+S_{ed})	Water/(Cement+Sediment)	WCS_{ed}

W/C+F	Water/(Cement+Filler)	WCF
W/C+S_{ed}+S	Water/(Cement+Sediment+Sand)	WCS_{ed}S
W/C+S_{ed}+S+S_p	Water/(Cement+Sediment+Sand+Superplasticizer)	W$CS_{ed}SS_p$

Graphical Abstract