Development of a 3D printable mortar with flash-calcined sediment

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ABSTRACT This study investigates the feasibility of using dredged sediment, which is now classified as waste, to partially replace Ordinary Portland Cement (OPC) in concrete 3D printing. The sediment used in this study was thermally treated using the flash calcination method. Mortars with varying flash-calcined sediment percentages (ranging from 0 to 20%) are studied and characterized in both fresh and hardened states. A manual gun device was used to test their printability (extrudability and buildability). The flow table test and the fall cone test were used to assess their workability and structural build-up, respectively. Furthermore, the compressive strength of the mortars was determined after 1, 7, and 28 days. The results show that it is possible to 3D print mortars containing up to 10% flash-calcined sediment while maintaining acceptable extrudability and buildability. Furthermore, no significant decrease in compressive strength was observed when flash-calcined sediment was added to the control mixture.

Keywords 3D printing, flash-calcined sediment, extrudability, buildability, compressive strength

I. INTRODUCTION

The preservation of natural resources, as well as the reuse and recycling of waste materials and by-products in the cement/concrete industry, has recently received a lot of attention in order to attain sustainable development. In parallel, the volume of dredged sediments in France each year is approximately 50 Mm^3 (Zhao et al., 2018). Nowadays, sediments are being recycled in a range of fields and industries, including road and underlays construction (Dubois et al., 2009) as well as brick production (Cappuyns et al., 2015; Hamer and Karius, 2002). Recent research has focused on reusing sediments as alternative materials in concrete to reduce the environmental impact of cement manufacturing and limit the consumption of natural resources required for concrete production (Amar et al., 2020; Aouad et al., 2012; Benzerzour et al., 2018; Zhao et al., 2018). These studies have demonstrated that incorporating sediments into cement, mortar, and concrete is extremely promising. Sediments, on the other hand, frequently contain contaminants and must be treated specifically to achieve the desired results. Recently, a novel and low-energy-consumption method known as "flash calcination" has been used to efficiently treat sediments by activating specific sedimentary phases (Scrivener et al., 2018).

Although many studies have been carried out on the implementation of dredged sediments in the construction field, none have yet been conducted on their use in concrete 3D printing. Hence, the goal of this research is to recycle dredged sediment to develop an environmentally friendly 3D printable waste-based mortar. The flash-calcined sediment is then used as a partial replacement for OPC to create a printable mortar that reduces cement consumption through waste material valorization. In this study, mixtures with various additions of flash-calcined sediment were developed and characterized.

II. MATERIALS AND METHODS

The materials used in this study were Ordinary Portland Cement (OPC) CEM I 52.5N provided by EQIOM (France), with a density of 3.15 g/cm^3 and a median particle diameter (D50) of 8.82 µm, fluvial sediment from Noyelles-sous-Lens (France), thermally treated by the method of flash calcination at 750 °C, with a density of 2.64 g/cm^3. Furthermore, two admixtures were used: CHRYSO® Fluid Optima 100 acting as a superplasticizer/high range water reducer (HRWR) with a dry content of 31%±1.5% and BELITEX® ADDICHAP acting as a viscosity modifying agent (VMA) in the form of a white powder.

Mixtures containing various percentages of flash-calcined sediment (0, 5, 10, 15, and 20%) were studied. Substitutions were made based on volume, and in order to uniquely evaluate the influence of sediment content on the fresh and hardened properties of the mixes, the water/binder ratio (w/b) was kept at 0.4 and the admixtures dosages were kept at 0.4% and 0.8% of the binder's weight for VMA and HRWR respectively. The composition of the tested mortars is shown in Table 1, where REF denotes the reference mixture without flash-calcined sediment (i.e., 100% OPC) and the others denote the mixtures containing flash-calcined sediment (FS) partially replacing OPC (e.g., FS10 corresponds to the mixture containing 10% FS and 90% OPC).

TABLE 1. Composition of mortars

Mixtures	REF	FS5	FS10	FS15	FS20
Sand (g)	850	850	850	850	850
OPC (g)	682.75	648.61	614.48	580.34	546.2
FS (g)	0	28.61	57	85.83	114.01
W/B	0.4	0.4	0.4	0.4	0.4
VMA (%)	0.4	0.4	0.4	0.4	0.4
HRWR (%)	0.8	0.8	0.8	0.8	0.8

To characterize the developed mortars in both their fresh and hardened stages, many tests were conducted. A manual gun device with a 2 cm circular nozzle diameter was used to assess the printability (extrudability and buildability) of mortars on a laboratory scale and subsequently a gantry Mini Printer for larger prints. The material was first defined extrudable when it exited the printing nozzle smoothly without causing any blockage or segregation, then buildable when it could resist its own weight and the weight of the following deposited layers without majorly deforming or collapsing. Then, the flow table test was carried out to assess the flowability/workability of the mortars according to the NF EN 1015-3 standard. In addition, the fall cone test was used to compute the yield stress and its evolution over time as well as the structural build-up of developed mortars. It was carried out according to the NF EN ISO 17892-6 standard as well as a previous study done by Baz et al. (Baz et al., 2021). The test uses a specific equation to calculate the yield stress values corresponding to a series of recorded penetration depths caused by an imposed load of a well-defined cone into the mortars. The used cone had a 30° angle and a total mass of 230 g. In this work, the cone's penetration depth into the mixed material placed in a circular container was measured using the same approach and methods as in (Baz et al., 2021) every 150 s for a total duration of 1320 s. Thereafter, the corresponding yield stresses (τ) in MPa were computed using the obtained penetration depths (h), as shown in Eq. (1), where (F) is the force generated by the cone mass:

$$\tau = (F\cos\theta^2) / (\pi h^2 \tan\theta) \quad (1)$$

Finally, the compressive strength of mortars was measured on regularly cast 4*4*16 cm beams at 1, 7, and 28 days, following the NF EN 196-1 standard, to better understand the effect of the binder composition on the hardened properties of the mortars.

III. RESULTS AND DISCUSSION

Using the manual gun device, it was shown that the increasing addition of sediment made the mixes drier and more difficult to extrude. Figure 1 shows the various printed mixes at laboratory scale. In comparison to the REF mix, FS5 and FS10 were easily extrudable and did not cause any blockage issues or printing difficulties. FS15 and FS20, on the other hand, were dry, difficult to extrude, and could not be printed properly. Based on these observations, the mix FS10 was chosen to be tested and printed on a larger scale with a gantry Mini Printer, as shown in Fig. 2.

FIGURE 1. **Printed mixes with the manual gun device (REF – FS5 – FS10 – FS15 –FS20)**

FIGURE 2. **FS10 mix printed with a gantry Mini Printer**

The flow table test (Fig. 3) showed that the flow diameter and workability of the developed mortars decreased linearly with sediment addition, which can be attributed to sediments' high water demand (Zhao et al., 2018).

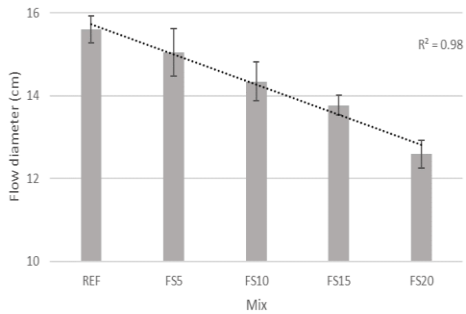

FIGURE 3. **Variation of flow diameter with the addition of flash-calcined sediment**

The fall cone test showed that variation of the yield stress of all mortars increases with time and that as the sediment content increases, the slope of the curves increases, implying that the addition of flash-calcined sediment leads to an increase in the structural build-up of mortars. In addition, the evolution of the yield stress with time can be established using a linear model with a high correlation factor (R^2), similarly to the findings of Bilal et al. (Baz et al., 2021) and Roussel (Roussel, 2006, 2005).

The compressive strength of mortars is shown in Fig. 5. FS5 and FS10 recorded strength values that are comparable to the REF mix, with FS5 exceeding REF at 1 and 28 days and FS10 exceeding REF at 1 and 28 days. However, higher substitution rates (15% and 20%) result in a slight decrease in compressive strength. These findings show that up to 10% of sediments can help improve the overall resistance by promoting the development of cement hydration (Dang et al., 2013).

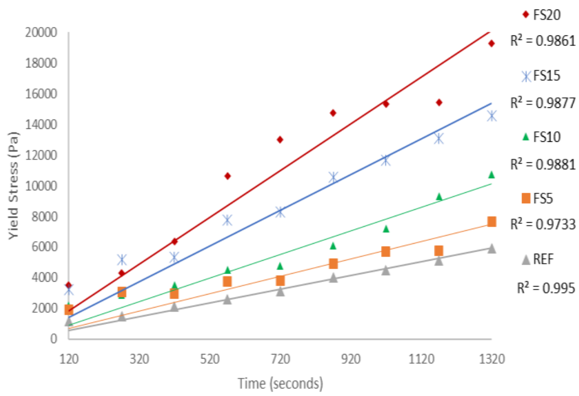

FIGURE 4. **Yield stress evolution of mortars with time**

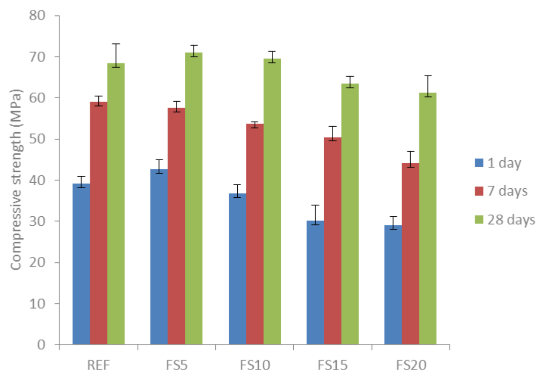

FIGURE 5. **Compressive strength of mortars**

IV. CONCLUSION

Flash-calcined dredged sediment had proven to be a viable and suitable material to replace OPC in the development of an eco-friendly 3D printable waste-based mortar. Mixtures with up to 10% flash-calcined sediment replacement of OPC (i.e., REF, FS5, and FS10) were printable (extrudable and buildable). A gantry Mini Printer was used to print FS10 on a greater scale. However, the addition of sediment reduced the flowability of mortars. In addition, the fall cone tests showed that the yield stress and structural build-up of all mortars with different sediment additions were linear over time. In terms of the hardened properties of the developed mixes, mortars containing

5% and 10% flash-calcined sediment had similar to higher compressive strength than the reference mortar, whereas mortars containing more sediment had lower compressive strength (15% and 20%).

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