applied sciences

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Article

Enhancing Cement Paste Properties with Biochar: Mechanical and Rheological Insights

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Supporting Materials

Methods:

The rheology of the pastes was studied using a rotational rheometer with co-axial cylinders provided by Malvern Pan'analytical Company (KINEXUS Pro+) by applying shear rates from $0.1\,s^{-1}$ to $200\,s^{-1}$ over six minutes. The gap between the inner and outer cylinder was 1.15 mm, while the gap between the base of the cup and the bob was set to 5 mm. A Peltier cell was used to keep the system temperature stable at 23 ± 1.0 ⁰C. The experimental procedure followed the ASTM C1749 standard [1].

Results:

The Bingham model (Eq. **Error! Reference source not found.**) is a rheological model used, for example, for cement pastes with non-zero yield stress and a linear relationship between shear rate and shear stress [2].

$$\tau = \tau_B + \eta_{pl}\dot{\gamma} \tag{1}$$

where τ is the shear stress (Pa), τ_B is the yield stress (Pa), η_{pl} is the plastic viscosity (Pa·s), and $\dot{\gamma}$ is the shear rate (s^{-1}). The yield stress determines the stress above which the material behaves like a fluid, while the plastic viscosity measures how easily the material flows as soon as the shear stress is higher than the yield stress [3].

Table S1. Summary of the main rheological parameters

ID	BC (%)	$\tau_B\ (Pa)$	n_{pl}	R^2
OPC	0	3.19	0.35	0.999
BC 1%	1	5.65	0.37	0.999
BC 2%	2	7.79	0.47	0.999
BC 3%	3	5.44	0.490	0.998
BC 5%	5	9.27	0.75	0.997
BC 7%	7	26.12	1.11	0.999

Figure S1 illustrates the effect of the biochar addition on the yield stress (τ_B) and plastic viscosity (η_{pl}) of all the samples. The plain cement reference sample has a τ_B value of 3.19 Pa , while the sample with a biochar content of 2 wt.% showed an increase of around

144%, reaching a τ_B of 7.79 Pa, while a decrement for the sample with 3% (5.44 Pa) was observed. Finally, the mix with a biochar content of 7 wt.% showed a higher yield stress of 26.12 Pa (+ 720% with respect to plain cement mortar). Biochar's effect on main rheological properties probably depends on the sample's preparation, the agglomeration of the particles and their content in each sample. The process of preparing samples matters and significantly influences the sample behavior both in the fresh state and in the hardened state [4,5].

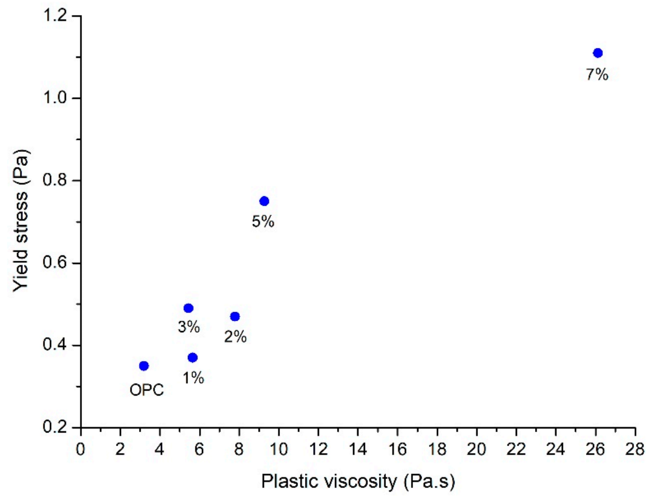

Figure S1. Yield stress in function of plastic viscosity and biochar content.

The yield stress in the 1% biochar-added samples is similar to that of plain cement. However, with higher biochar additions, the yield stress increases due to the greater quantity of particles and the potential interlocking effect, along with a larger number of agglomerates that need to be broken. A low yield stress value is targeted to reach high flowability and high filling ability, whereas a moderate viscosity is important to keep a good cohesiveness and to limit segregation of the mix [6]. Ordinary concrete has a rather high yield stress value (around 500 Pa), while in self-compacting concrete, the yield stress varies from a few Pa to less than 60 Pa [7].

After biochar addition and without any dispersant/superplasticizer, biochar cement pastes yield stress is close to that of self-compacting concrete. Adding particles, specifically those with large specific surface areas, increases yield stress and plastic viscosity due to the higher water demand. Contrarily to yield stress, the plastic viscosity continuously increases with the addition of biochar from 0.35 Pa·s to 1.11 Pa·s, for plain cement and after 7% B addition, respectively (Table S1, Figure S1), since the viscosity is directly influenced by the volume of solids in the mix [8]. In fact, plain cement paste can be seen as a water suspension of cement particles surrounded by a thin layer of water around cement particles. This layer reduces friction between particles and lubricates them, allowing the paste to flow easily. Fine biochar particles absorb a lower amount of water with respect to coarser ones (0.94 ± 0.02 g of water for 1 g of dry biochar). Thus, the local w/c is not altered at the same rate as with coarse biochar particles. However, fine biochar particles are porous and absorb a certain quantity of water. Fine biochar particles can also trap water within interparticle spaces formed because of their agglomeration. This behavior also reduces the available water for lubrication [9].

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