Int. J. Environ. Res., 10(2):203-216, Spring 2016
ISSN: 1735-6865

Repair Mortars and New Concretes with Coal Bottom and Biomass Ashes Using Rheological Optimisation

Brás, A.[1*], Faustino, P.[2]

[1]Department of Architecture & Civil Engineering, University of Bath, UK

[2]Mouchel (Scotland TranServ), Glasgow, UK

Received 19 April 2015; Revised 16 Jan. 2016; Accepted 20 Jan. 2016

ABSTRACT: The objective of the present work is to analyse the potential of using non-classical additions in concrete and mortar compositions such as coal bottom ash (BA) and biomass ash (Bio), as partial replacing binder of ordinary Portland cement. It is intended to deal with production of these type of wastes and its accumulation and contribute to the minimisation of carbon and embodied energy in construction materials. The aim is to identify the concrete and mortars formulation types where it is possible to get more benefit by incorporating BA and Bio. Based on the optimisation of the rheological properties of cement-based materials, mortars with repair function and concrete compositions were developed including 0%, 10%, 15% and 20% of BA and Bio as cement replacement. An assessment of the evolution of relative concrete compressive strength was calculated as a function of the relative solid volume fraction of several concretes. BA compositions present low resistance to high flow rates, increasing the ease of placement and vibration. BA seems to present more filler and pozzolanic effect when compared with Bio. BA mortars fulfil the compressive strength and stiffness requirements to be used as repair mortars, allowing the replacement of 15% or 20% of cement by an industrial waste. This by-product is able to work in the development of the mortar and concrete microstructure strength adopting a much more sustainable solution for the environment.

Keywords: Biomass and coal bottom ashes,Repair mortar,Concrete,Rheological behaviour and yield strength

INTRODUCTION

The increasing need of ecological and energy-efficient solutions in construction is leading researchers and decision makers towards the study and implementation of alternative materials and systems. Demand for materials in construction today is largely driven by the relatively low cost of materials compared to labour in European countries since it is potentially cheaper to standardise a building design than to design for individual element efficiency (Torgal *et al*., 2013). However, if clients specifies material efficiency within the project brief all parties in the construction supply chain can co-operate to deliver the project to minimise excess material usage. Avoiding over specification should reduce material purchasing costs, energy and carbon and thus can become a selling point as a sustainable building. One sixth of the world's CO_2 emissions arise from producing steel and cement, which are made efficiently, but are used inefficiently, particularly in construction. In reinforced concrete (RC) structures, being concrete the most widely used material in construction, one of the main strategies preconized so far is clinker partial replacement with industry by-products.

The use of classic additions, considered as supplementary cementitious materials (Lothenbach *et al*., 2011), such as: limestone filler; blast furnace slag; fly ash; or silica fume, has had its practice for decades since these supplementary cementitious materials gave different properties to the concrete making it adjustable to different environments, namely those where chemical action on concrete was considered aggressive (Coutinho and Gonçalves, 1994). However, over time several changes have been taking place concerning the different industries and their resources which has brought new solutions to society. These industries have brought nevertheless new challenges in how to deal with production of waste and its accumulation.

Two of the compounds that are part of the waste of these industries are: coal bottom ash (BA), as a result of coal-fired electricity production; and biomass ash (Bio), which is obtained from the combustion of worldwide existing biomass.

*Corresponding author E-mail: a.a.armada.bras@bath.ac.uk

As a by-product with chemical composition similar to fly ash, coal bottom ash is, nowadays, a by-product that has not being used for decades, which is a great concern for industries of production of coal-fired electricity, namely in Europe. The accumulation of this waste is an environmental and storage problem still unresolved.

This by-product is therefore an object of study towards its inclusion in concrete production, since it may be properly recycled as it may additionally reduce the use of clinker, whose production generates significant CO_2 emission. The incorporation of coal bottom ash as a partial replacement of clinker could also reduce the consumption of cement and the energy required to produce it.

From a different conjuncture, and resulting from a new approach to energy generation, there is today a production of a by-product that results from the use of biomass combustion. The resort to biomass as an energy source is presently an already implemented option before classic sources such as oil, coal or natural gas. Biomass consumption generates wastes of which the designated biomass ashes are part of and are being tested as a binding material for concrete production, replacing clinker partially. Whether or not coal bottom ash and biomass ash are suitable in all aspects to be part of concrete as a binding material, several studies (Cheriaf *et al*., 1999, Canpolat *et al*., 2004, Rajamma *et al*.,2009, Wang *et al*., 2008, Wang et at., 2008b, Maschio *et al*., 2011) have contributed to show that there is a possibility to include these by-products in hydraulic pastes and concrete production so that less quantity of clinker is used. With regard to mortars and concrete properties it is nevertheless important to analyse their performance in fresh state in order to understand their range of application, which means that the parameters related to the rheological behaviour are herein the main issue.

The goal of the present work is to analyse the potential of using non-classical additions in concrete and mortar compositions such as: coal bottom ash (BA) and biomass ash (Bio). The adopted methodology was the following:

- Assessing the evolution of the relative concrete compressive strength calculated as a function of the relative solid volume fraction of several concretes, with different compositions including several addition types - to identify the concrete and mortars formulation types where it is possible to get more benefit by incorporating biomass ash and coal bottom ash, as partial replacing binder of ordinary Portland cement.

- Development of mortars and concrete compositions (0%, 10%, 15% and 20% of biomass ash or coal bottom ash as cement replacement).

- Analysis of fresh state behavior in a transient state.
- Analysis of hardened state properties: SEM images, compressive strength, dynamic elastic modulus and porosity at 28 days and 60 days for mortars and concretes.

- Definition of the best range of application for biomass and coal bottom ashes in repair mortars and concretes.

Yammine et al. (Yammine *et al*., 2008) demonstrated that it is possible to significantly affect and optimize the rheology of a given concrete by changing the aggregates content of the mixture. They showed that decreasing the aggregates volume fraction from 72% to 65% was sufficient to transform the ordinary rheology of High Performance Concretes (HPC) into a Self-Compacting Concretes (SCC) without an impressive decrease in the mechanical strength of the hardened concrete.It is known that there is a proportion between the yield stress of suspensions (concrete mixture) and the yield stress of its suspending fluid (constitutive cement paste). Krieger–Dougherty relation for apparent viscosity relates the rheological properties of the suspending fluid and the volume fraction ϕ of the particles to the rheological properties of the mixture (Krieger and Dougherty, 1959, Geiker *et al*., 2002). The general form of these relations is:

$$\tau_0^{Conc} = \tau_0^{cp} f(\phi/\phi_m)$$

where τ_0^{Conc} and τ_0^{cp} are respectively the yield stresses of the concrete and the cement paste and ϕ_m is the maximum packing volume fraction.In (Yammine *et al*., 2008) the researchers tried to apply to their results the packing model developed by De Larrard (Larrard, 1999) which predicts that the mechanical strength *fc* is proportional to the following:

$$fc = (1-(\phi/\phi m)^{-1/3})^{-r} \qquad (5)$$

with r between 0.13 and 0.16 and then, they study the evolution of the ratio between the measured mechanical strength and the mechanical strength of the reference concrete as a function of the granular skeleton volume fraction (Fig. 1). It can be seen that, for a 7% decrease in granular skeleton volume fraction that generates a decrease in yield stress of almost two orders of magnitude, only a decrease of less than 10% of the mechanical strength is observed. However, the questions of the effects of the cement substitution by an alternative powder were not considered here.

Thus, based on the results presented by other authors (McNally, 2012, Sideris and Anagnostopoulos,

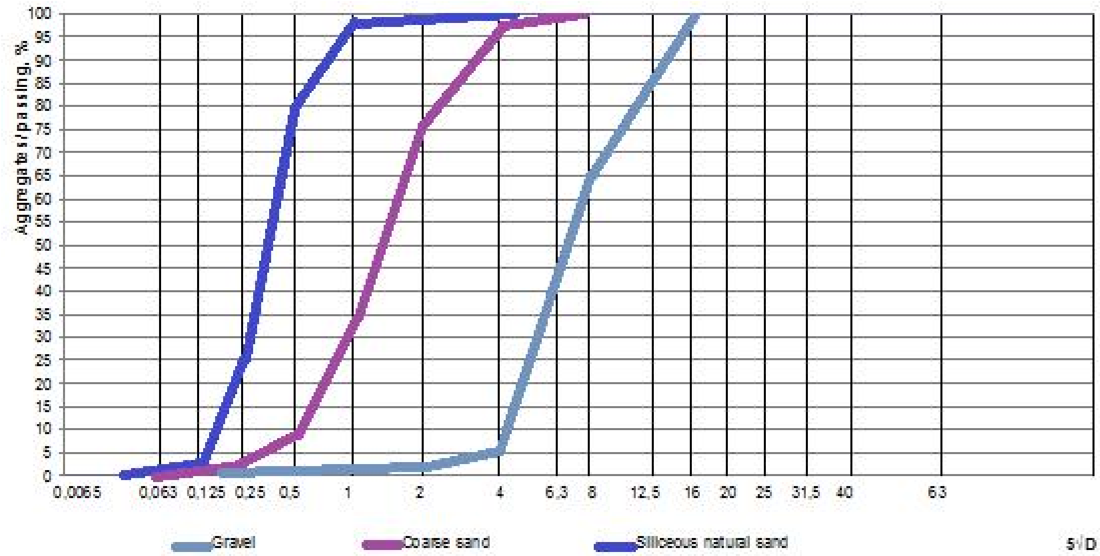


Fig. 1. Relative mechanical strength (ratio between mechanical strength and mechanical strength of the reference concrete) as a function of the aggregates volume fraction (Krieger and Dougherty, 1959)

Table 1. Type of concrete and incorporation ratio of several additions as cement substitution used to produce the results presented in Fig. 2.

Type of concrete	incorporation ratio (%)	Type of concrete	incorporation ratio (%)
OPC	0	C BFS - CEM II/A–L	0
C FA	40		50
	50		70
C SF	8	C BFS - CEM II/A–V	0
C BFS - CEM I	60		50
OPC+4% SF	4		70
C BFS - CEM II/A–L	0	SCC + x% Filler	20
	50		30
	70	SCC CEM II B-L + x% SF	4

2013, Marques *et al*., 2012, Marques *et al*., 2010), the aggregate volume fraction and the maximum packing volume fraction were calculated for eleven different concrete compositions. Then, the relative compressive strength (the strength relation between a concrete and concrete reference: CEM I 42.5 R with w/b=0.43) was calculated as a function of the relative solid volume fraction for each concrete. The objective was to check the limit of concrete granular content that minimize the contribution of the aggregates to the mixture yield stress and, at the same time, does not significantly affect the relative compressive strength. Those results are presented in Fig. 2.

All the selected concrete compositions present a w/b between 0.43 and 0.48 and several concrete compositions were selected based on the type of addition as cement substitution: fly ash (FA), silica fume (SF), blast furnace slag (BFS) and limestone filler (Filler) McNally (2012), (Sideris and Anagnostopoulos, 2013), (Marques *et al*., 2012), (Marques *et al*., 2010). Different incorporation ratios as cement substitution are presented using bubble sizes (small sizes means less addition). The De Larrard packing model predictions was developed using the C Ref (CEM I 42.5 R with w/b=0.43) and that model curve is also presented in Fig. 2. Table 1 presents the eleven types of concrete selected.

The previous results presented in Fig. 2 show that OPC, OPC+ SF=4% or 8%, C BFS –CEM II /A-L, SCC-20% of Filler and SCC CEM II B-L +SF=4% are the ones that fit with the De Larrard packing model predictions. If an addition different from SF or Filler is used, then the relative compressive strength tends to decrease as long as incorporation ratio increases,

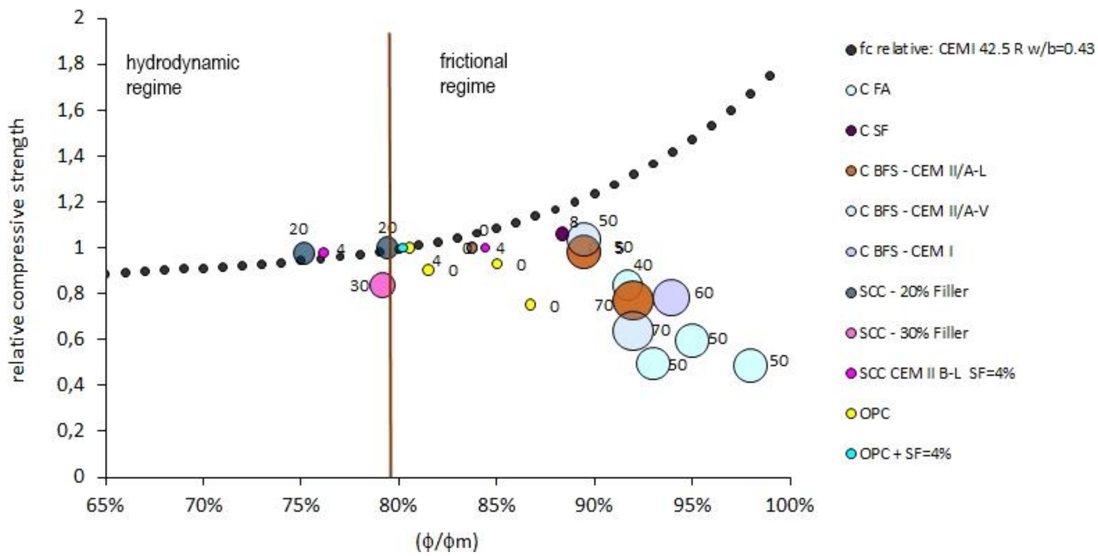


Fig. 2. Relative compressive strength as a function of the relative solid volume fraction for several concrete compositions. The legend presented near each bubble is the percentage used as cement replacement

meaning as effecting reduction of concrete strength. Besides this, it can be observed that all the analysed concretes present a relative solid volume fraction between 75% and 98%, where the lowest values are mainly for SCC types – where the incorporation of additions seems to work.

Taking into account that there is a critic ϕ/ϕ_m that separates the influence of hydrodynamic interaction between aggregate particles and the frictional contacts between those particles (which represents a huge influence on the concrete rheological behaviour), the relative solid volume fraction was adopted since it can be compared to the critical value deduced from the mono-sized spheres, where ϕ/ϕ_m =0.79, instead of dealing with the value of the volume fraction itself. Thus, according to the previous results, if granular content is below the transition between frictional regime and hydrodynamic regime it only guarantees that the contribution of the aggregates to the yield stress of the mixture will be low.In fact, the SCCs presented in Fig. 2 fit with the previous statement. OPC concretes are on the right side of a vertical line that passes in ϕ/ϕ_m =0.79.

Based in the previous results, the incorporation of biomass ash or coal bottom ash is probably optimized if they are used in a SCC formulations, where the relative compressive strength should decrease less in comparison to non-SCC concretes, where the deviation from the De Larrard packing model predictions is much higher. According to this previous results, it is possible to get more benefit by incorporating biomass ash and coal bottom ash if they used in mortars and concretes formulations with self-levelling behaviour. The experimental program was developed based in this assumption, by using higher quantities of cement (kg/ m^3 of mortar or concrete) and developing mortars that could be used in structural repair solutions and development of SCC.

MATERIALS & METHODS

In this study, two different additions were tested in cement based mortars, as a partial cement substitute in contents of 10, 15 and 20 wt.%. The reference mortar (M Ref) is made of Portland cement (CEM type I 42.5R, according to EN 197-1 2000) as a binder and a siliceous natural sand in the presence of a high range water reducer (HRWR) and water/binder (w/b) = 0.30. The formulation for the control concrete mixture was determined using the Baron-Lesage method. The control concrete mixture (C Ref) constitution involves Portland cement (CEM type I 42.5R) as binder, a siliceous natural sand and two types of crushed limestone as aggregate. Biomass ash and coal Bottom ash were also used as a partial cement substitute in contents of 10%, 15% and 20% wt. The constituents and properties of the cement, biomass and coal bottom ash used in this work are presented in Table 2.

The sulfate content of Bio is higher than BA which enhance that Biomass ash could slightly contribute to degradation of Portland based-systems – in comparison with coal bottom ash- through mechanisms of expansion and cracking during sulfate attack. However, since the sulfate content of CEMI is higher than the tested ashes (2.9%) we decided to evaluate the effect of replacing cement by them.

All mortars and concrete compositions were defined with the same w/b ratio and used the same fine sand, BA and Biomass proportions (Tables 3 and 4). Primarily, mortars were designed and mixed with

Table 2. Portland cement OPC (CEM I 42.5R), coal bottom ash (BA) and biomass ash (Bio). Constituents and properties – wt%

	CEM I (OPC)	Coal bottom Ash (BA)	Biomass Ash (Bio)
clinker (%)	95	-	-
lime filler (%)	-	-	-
Loss on ignition (%)	3.17	5.1	19.2
SiO_2 (%)	19.45	49.7	40.2
Al_2O_3 (%)	4.17	22.6	10.1
Fe_2O_3 (%)	3.51	6.7	3.1
CaO (%)	62.42	6.9	15.8
MgO (%)	2.2	4.9	3.8
Cl (%)	0.03	<0.1	<0.1
SO_3 (%)	2.9	0.3	2.3
CaO free (%)	1.39	0.26	0.47
Density (g/cm^3)	3.11	2.05	2.16
Specific surface area (cm^2/g)	4408	3145	3343

Compressive strength (MPa)	CEM I (OPC)
2d	31.9
7d	45.5
28d	56.9

Table 3. Mortar compositions with OPC (CEM I 42.5R) and with Biomass ash or coal bottom ash as binder – kg/m^3

	M Ref	M Bio 10	M Bio 15	M Bio 20
Type of cement	CEM I	CEM I	CEM I	CEM I
Cement dosage	515	464	438.3	412.5
Biomass ash / Coal bottom ash	-	51.5	77.3	103
sand 0.125-1 mm	1562.5	1562.5	1562.5	1562.5
HRWR (% binder wt)	0.4/ 4.0	0.4/ 4.0	0.4/ 4.0	0.4/ 4.0
w/b	0.30/0.26	0.30/0.26	0.30/0.26	0.30/0.26

Table 4 . Concrete compositions with OPC (CEM I 42.5R) and Biomass ash or BA as binder – kg/m^3

	C Ref	C Bio 10	C Bio 15	C Bio 20
Type of cement	CEM I	CEM I	CEM I	CEM I
Cement dosage	450	405	390	330
Biomass ash / Coal bottom ash	-	45	68	90
sand 0.125-1 mm	309	309	309	309
sand 0.25-2 mm	525	525	525	525
gravel 4-8 mm	771	771	771	771
HRWR (% binder wt)	0.4	0.4	0.4	0.4
w/b	0.43	0.43	0.43	0.43

HRWR= 0.4% and were then tested for those different compositions. However, the fresh state results lead to an option of testing mortars with more HRWR. Therefore, it was decided to test the same mortar compositions but with more HRWR (4% by cement weight), even knowing that the benefit from an economical point of view was reduced. The concrete compositions were developed selecting the smallest HRWR dosage tested (0.4%), in order to minimise the costs.

In order to obtain the yield stress of fresh state mortar and concretes, despite different tests might be suited – namely those done with a rheometer – the tests chosen for the presented work included only the use empirical measurements such as the flow table (for mortar) and the inclined plan (for concrete) which, even if of indirect approach, these tests allow a simple way of measuring the yield stress.

The rheological behaviour of the fresh mortars and concretes was studied and compared to that of a reference ash free production in order to evaluate the effect of ash addition on rheological behaviour and mechanical strength. The analysis was developed by using analytical correlations between empirical measurements such as flow table test and inclined plane test to allow the identification of yield stress and quantify the workability of the mortars and concretes tested. As mortar and concrete rheometers do not yet give any absolute value of the rheological parameters such as yield stress (Ferraris *et al*., 2004, Roussel *et al*., 2007, Roussel, 2006, Roussel *et al*., 2005, Flatt *et al*., 2006), simple empirical tests will be used along with their analytical correlation with yield stress. These tests give only access to the value of the yield stress of the studied materials - the value of the stress that has to be applied to the material to initiate flow. However, it is the most important rheological parameter from a casting/placing point of view (Khayat *et al*., 2009, Khayat *et al*., 2010).

Flow table test was adopted to determine the "workability" of fresh mortar (Fig. 3) and the experimental measurements were done following the description in ASTM C230. The spread was measured for all mortar compositions for different resting times. After that, an attempt to estimate the yield stress was done using spread (Coussot *et al*., 1996, Domone, 1998, Senff *et al*., 2009, Roussel, 2007).The yield stress τ_0 can be determined by (eq. 1), based in ASTM mini cone for cement paste Roussel (2006), (Roussel *et al*., 2005), (Flatt *et al*., 2006):

$$\tau_0 = \frac{225 \rho g V^2}{128 \pi^2 R^5} \qquad (1)$$

with ρ the density of the tested cement paste, V the tested volume and R the spread radius.

Khayat (Khayat *et al*., 2010) tested several Self Compacted Concretes (SCC) mixtures of various compositions and demonstrate that yield stress characteristics determined using the inclined plane method are comparable to those measured using a concrete rheometer. Thus, the same procedure was adopted in our tests.The concrete compositions were developed selecting the smallest HRWR dosage tested in mortars (0.4%), in order to minimise costs. The workability of those concretes was evaluated based in a novel inclined plane (IP) method (Ferraris *et al*., 2004, Roussel *et al*., 2007) that also enables the evaluation of the structural build up at rest.

This test involves placing concrete in a cylindrical mould measuring 60 mm in height and 120 mm in diameter, on a horizontal plate of Plexiglas. The plate is then lifted slowly (over 10s) to initiate the flow of the material, as illustrated in Fig. 4. The corresponding angle necessary to initiate the flow is used to determine the static yield stress, $IP\tau_{0rest}$ in Pa as follows:

$$IP\tau_{0rest} = \rho g h \sin\alpha \qquad (2)$$

Where: ρ is unit weight of tested material in kg/m^3, g is the gravitation constant that equals 9.81 m/s^2, h is the characteristic mean height in mm of the slumped sample, and α is the critical angle of the inclined plate (in degree) when the sample starts to flow. The h value is the mean of five heights of the slumped sample; four of them at measured in the circumference of a middle circle of the slumped spread, and one at the centre.Although without a direct relation with durability, mortar/ concrete compressive strength is a reference parameter as regards the performance of a mortar/ concrete composition.

In order to determine mechanical characteristics of the formulated mortar, a testing campaign was undertaken and all 6 specimens of each mortar composition were submitted to compressive strength tests following standard NP EN 1015-11. Concrete compressive strength was carried out following the standard NP EN 12390-3 (2009). The experimental campaign included concrete compositions subjected to compressive tests at the age of 28 days (3 specimens of each). In order to understand the previous results, the mortars and concretes open porosity was measured by vacuum and hydrostatic weighting based on EN 1936:2008.

The experimental campaign included mortar and concrete compositions subjected to dynamic elasticity modulus tests and porosity determination tests at the ages of 28 and 60 days. The mortars open porosity was measured by vacuum and hydrostatic weighting based on EN 1936:2008.

Fig. 3 . Flow table test used in the analysis of fresh mortars

Fig. 4. Inclined plane test

RESULTS & DISCUSSION

The relation between yield value in mortars and spread diameter for the following compositions is presented in Fig. 5: M Bio 10, M Bio 15, M Bio 20, M BA 10, M BA 15 and M BA 20 with HRWR=0.4% and 4%.

For a resting time of 5 minutes after mortars' preparation, the previous figures show that yield stress values substantially decrease if HRWR increases from 0.4% to 4% in mortars. BA-cement mortars present much lower yield stress value than the mortars with biomass, especially for HRWR= 4%. Based on the previous results, it was decided to keep studying the mortars with HRWR= 4%.

Four tests were performed after different periods of rest to evaluate the rate of increase in IPτ_{0rest} at rest. For the concretes herein studied, the resting times were 15, 30, 45, and 60 minutes. The results of yield stress evolution with resting time are presented in Fig.6. It includes data for the concrete reference (CEM I), for the concretes with Biomass ash and coal bottom ash (10, 15 and 20% of cement substitution). Those results were also compared with a concrete that use Portuguese traditional cement (CEM II B-L 32.5N) - C CEM II B-L 32.5N using the same proportions as the one used in C Ref.

The results show that static yield stress evolution of those blended cement concretes are between C Ref and C CEM II B-L 32.5N, which is in fact the one that present highest casting ability for an increasing resting time. C BA family presents the second best behaviour and it seems that a simple addition of 10% of coal bottom ash in an OPC composition enables an increasing of its workability.

C Bio seems to behave as well as C Ref with an increasing resting time. However, in the first 15 minutes at rest, the results are poor when compared to C Ref behaviour. In this range (0-15min) the loss of workability increases if Biomass ash dosage increases in the concrete composition.

The following figures present the static yield stress evolution with the resting time, for an increasing incorporation ratio of biomass or coal bottom ash in concretes (Fig. 7 a) and b)) and in mortars (Fig. 8 a) and b) and 9 a) and b)).

Concrete results (Fig.7) with biomass ash show that yield stress substantially increases for an increasing incorporation ratio. For different resting times, the changes in yield stress seem to disappear especially if more than 10% of biomass is used. However, concrete yield stress tends to decrease if coal bottom ash is used and for these compositions the differences between values is relevant for distinct resting times. These yield stress values in C BA are much lower than in C Bio compositions.

Figs 8 and 9 show that the incorporation of biomass ash leads to an increase of mortar yield stress value (when compared to MRef) and its stabilization for any biomass quantity added beyond that dosage. Thus, it seems that even when more superplasticizer is added (from 0.4 % to 4%) its effect here in not expressive. However, mortars with coal bottom ash always tends to present less yield stress if more coal bottom ash is added to mortar composition.The results of dynamic elasticity modulus simultaneously with compressive strength are shown in Fig. 10 -14, as well as the results of the porosity tests.

At 28 days, the incorporation of 15% or 20% of coal bottom ash (BA) or Biomass ash as partial replacement of ordinary Portland cement leads to equivalent compressive values. However, those

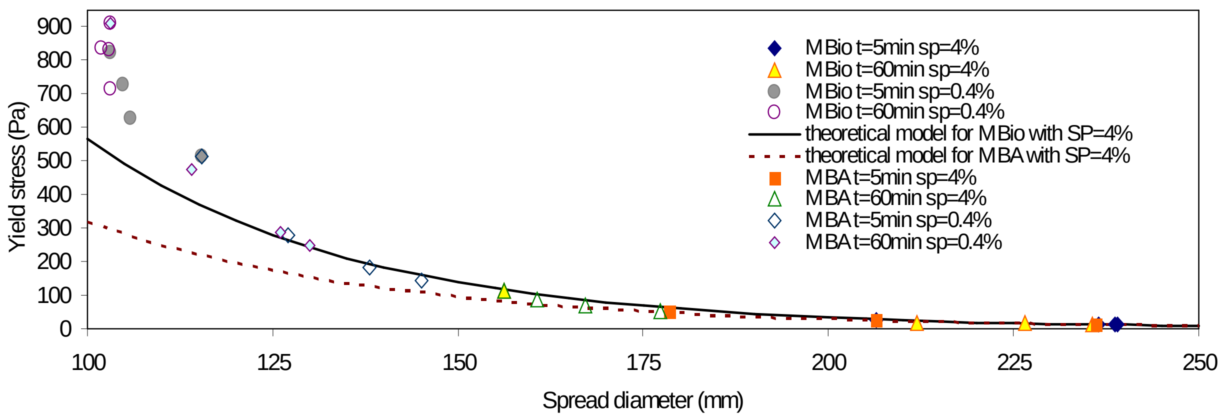


Fig. 5 . Relation between Yield Stress τ_0 and Spread Diameter. Cement mortars with Biomass and coal bottom ash (from 10% to 20% for a resting time of 5 and 60 min). The theoretical curves were obtained from the models expressed by Eq. 1

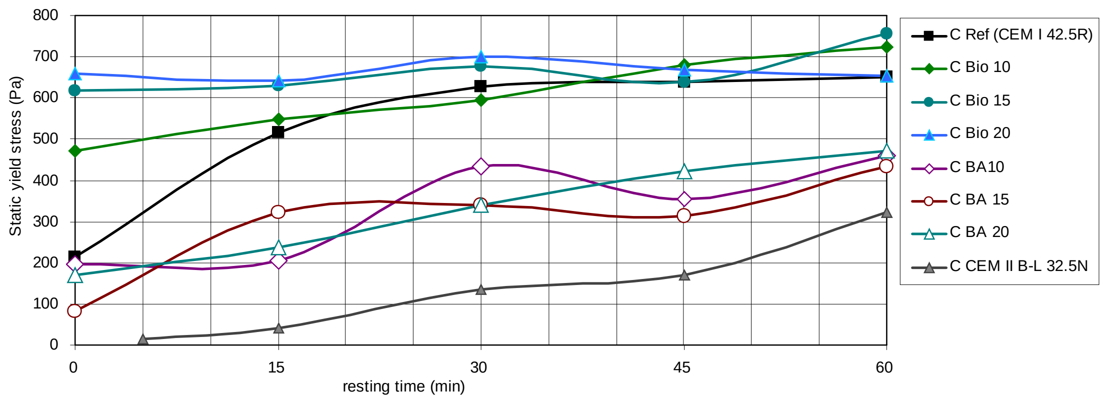


Fig. 6. Variation of static yield stress with time using inclined plane test for the concrete compositions: C Ref, C Bio 10, C Bio 15, C Bio 20, C BA 10, C BA 15, C BA 20 and C CEM II B-L 32.5N

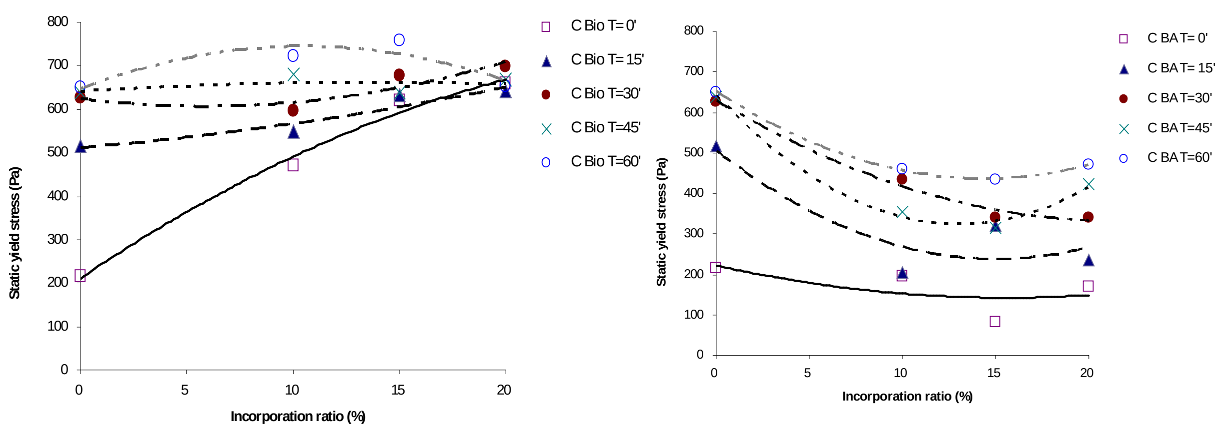


Fig. 7. Static yield stress evolution with an increasing incorporation ratio of biomass or coal bottom ash for in concrete mixes: a) C Bio b) C BA

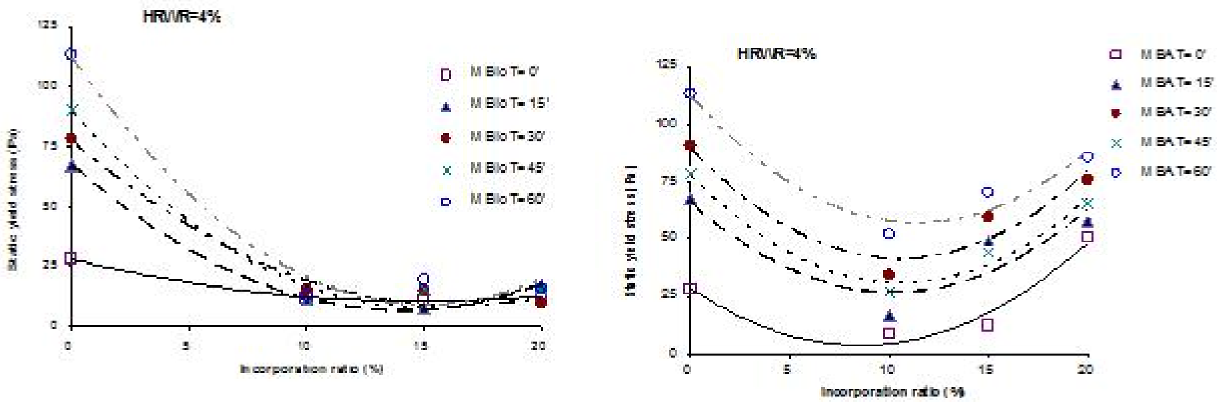


Fig. 8. Static yield stress evolution with an increasing incorporation ratio of biomass or coal bottom ash for M Bio and M BA (HRWR=4%). a) M Bio b) M BA

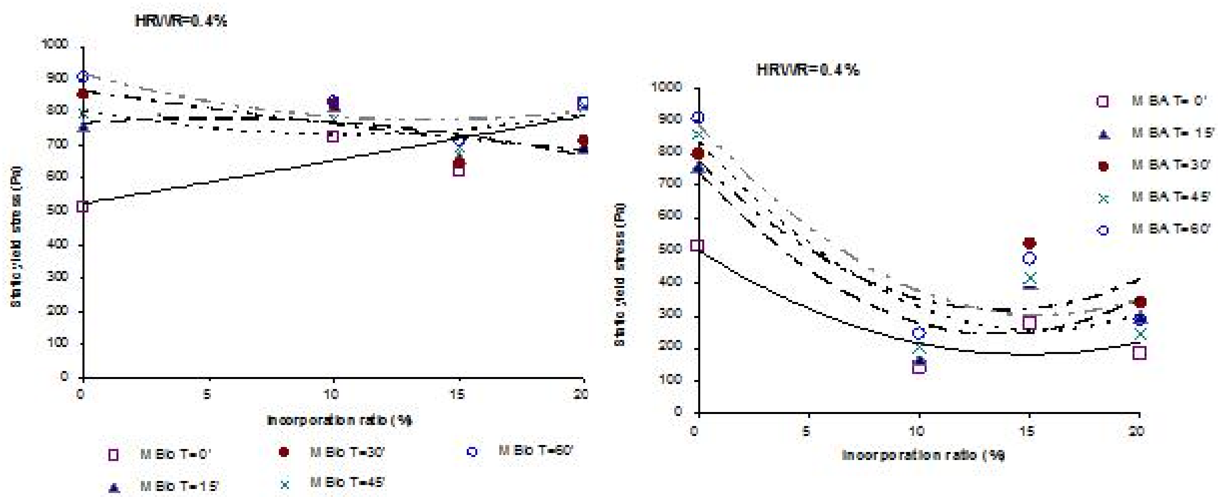


Fig. 9 . Static yield stress evolution with an increasing incorporation ratio of biomass or coal bottom ash for M Bio and M BA (HRWR=0.4%). a) M Bio b) M BA

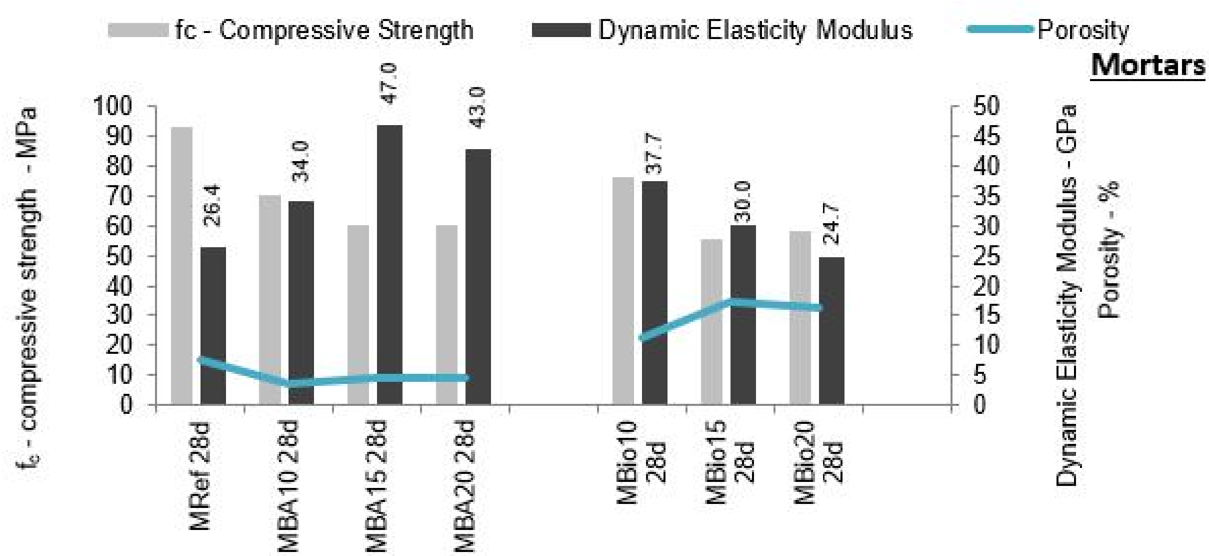


Fig. 10 . Compressive strength, dynamic elasticity modulus and porosity results of mortars specimens at the age of 28 days (HRWR= 0.4%)

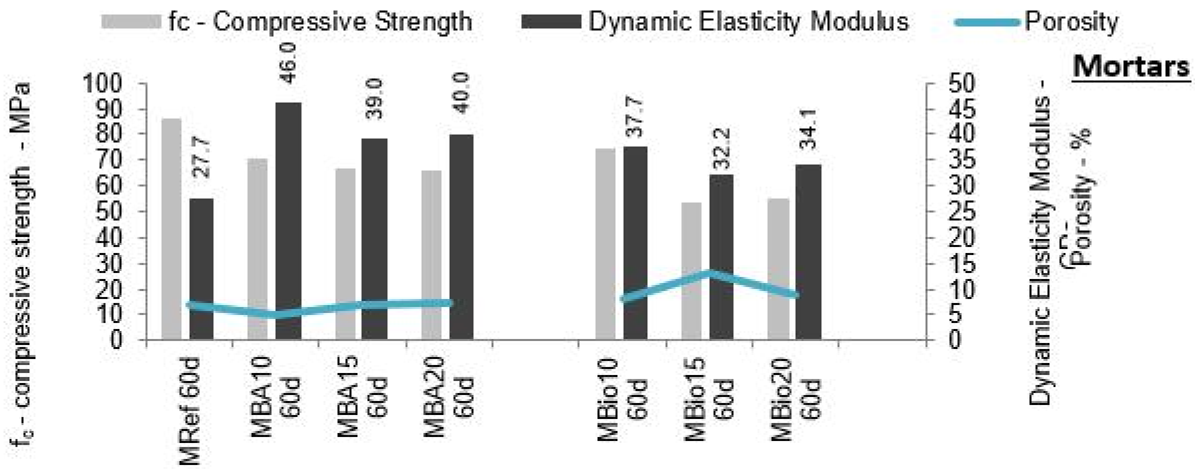


Fig. 11. Compressive strength, dynamic elasticity modulus and porosity results of mortars specimens at the age of 60 days (HRWR= 0.4%)

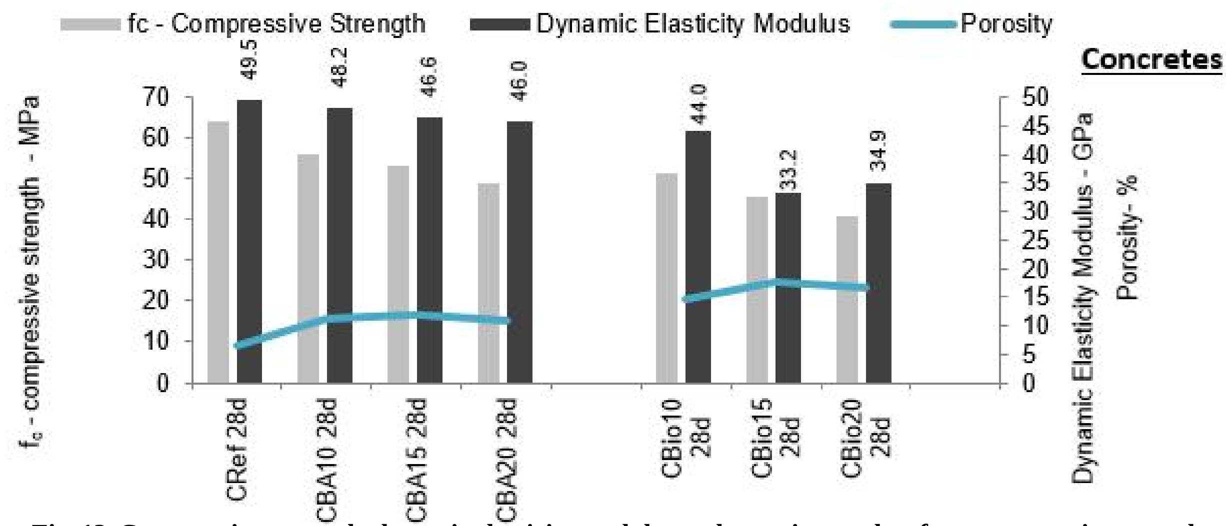


Fig. 12. Compressive strength, dynamic elasticity modulus and porosity results of concrete specimens at the age of 28 days (HRWR= 0.4%)

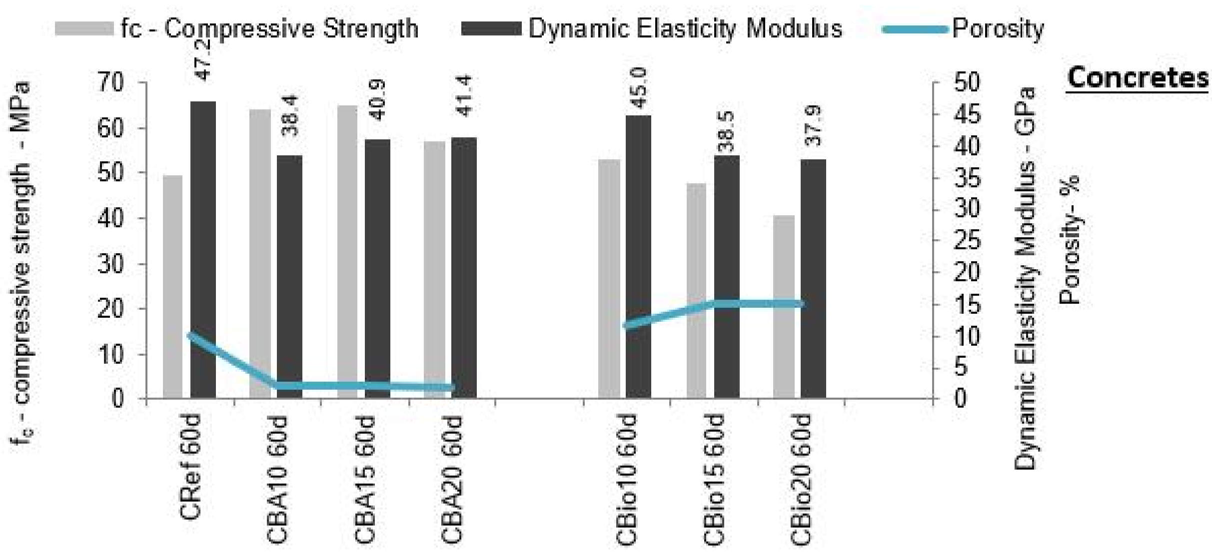


Fig. 13 .Compressive strength, dynamic elasticity modulus and porosity results of concrete specimens at the age of 60 days (HRWR= 0.4%)

strength values are almost 40% lower than the compressive value of the reference mortar. Dynamic Elasticity modulus tends to increase with the addition of BA in the mortar composition, probably due to the incorporation of coal bottom ash which are able to work as a filler and leads to the reduction of porosity values. An increase of porosity leads to a reduction of elasticity modulus of mortars with biomass ash. At 60 days of age the results are not so different for compressive strength, elastic modulus and porosity. Nevertheless, the presented results show that all BA mortars fulfil the compressive strength and stiffness requirements to be used as repair mortars, allowing the replacement of 15% or 20% of cement by an industrial waste. This by-product is able to work in the development of the mortar microstructure strength adopting a much more sustainable solution for the environment.

For the concrete compositions tested, the compressive strength of C BA tends to decrease with the increasing of coal bottom ash at 28 days. There is a decrease of 15 MPa in mechanical strength when 10% of these coal bottom ashes are added. Beyond that incorporation ratio the decrease of mechanical strength is less expressive. However, at 60 days there is an expressive strength increase of 1.15 to 1.20 times for the concretes with coal bottom ash, enhancing its pozzolanic effect. That effect probably works together with coal bottom ash filler effect, detected by the decrease of CBA porosity values from 28 to 60 days. The concretes with biomass ash (CBio) do not present significant benefits when compared to CRef. However, the replacement of 10% of cement by biomass ash seems to lead to similar behaviour as CRef.

In order to enable the comparison between the behaviour of C Bio - M Bio and C BA - M BA, normalized static yield stress was adopted taking into account the value of yield stress of the C Ref and M Ref at a resting time equal to zero.The behaviour of those cement compositions with biomass and coal bottom ash are presented in Figs. 14 and 15, for an increasing resting time using HRWR= 0.4% in mortars and concretes.

The partial replacement of Portland cement by coal bottom ash in concretes and mortars originates a binder with excellent response in the fresh state. Both BA mortars and concretes have higher workability when compared to biomass ash or traditional mortars and concrete compositions, presenting stabilized normalized yield stress values along the first hour after mortar and concrete production. The incorporation of coal bottom ash in concrete allows its use in the casting of slabs and walls, where dominates the pressure on the formwork. These concretes present low resistance to high pump speeds, namely a low plastic viscosity, making them particularly attractive for use in situations where there is a need for pumping concrete to a high altitude.

The low resistance to high injection speeds also enable the use of BA mortars as a repair material in beams concrete jacketing, allowing an easy spread of mortar in the formwork. The previous figures show that generally, BA increase concrete/mortars workability, and their yield stress becomes at least 1.5 – 2 times smaller than the reference blend (M Ref or C Ref). However, the same does not happen with biomass ash compositions, where increasing their quantity decrease mortar and concrete workability. The reason why mixtures with BA present higher workability may be explained by the shape of size of grains, since coal bottom ash present spherical particles with dimensions ranging from <100 μm, enabling a better particle rearrangement at mortars and concretes in the fresh state. From the other side, biomass ash present irregular large sized clusters of particles which could difficult the development of strong connections between particles. Fig. 16 a) and b) present a SEM micrographs

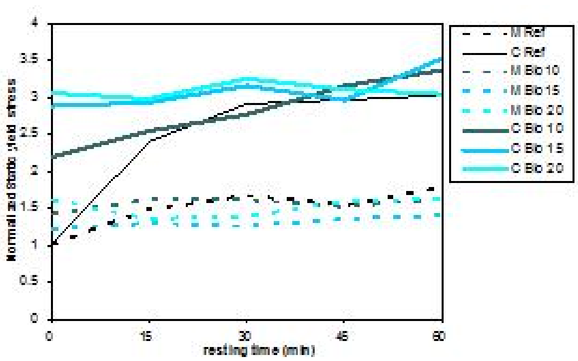


Fig. 14. Evolution of normalized static yield stress with resting time for mortars and concretes with biomass ash using HRWR= 0.4%.

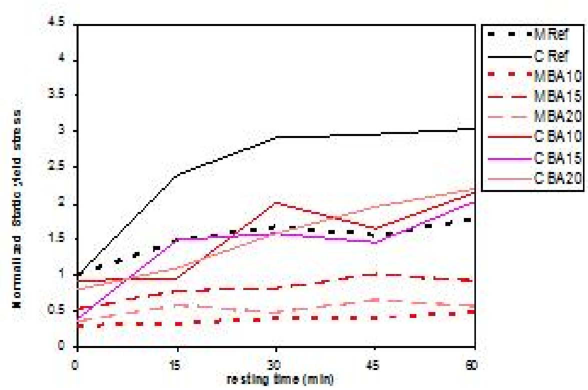
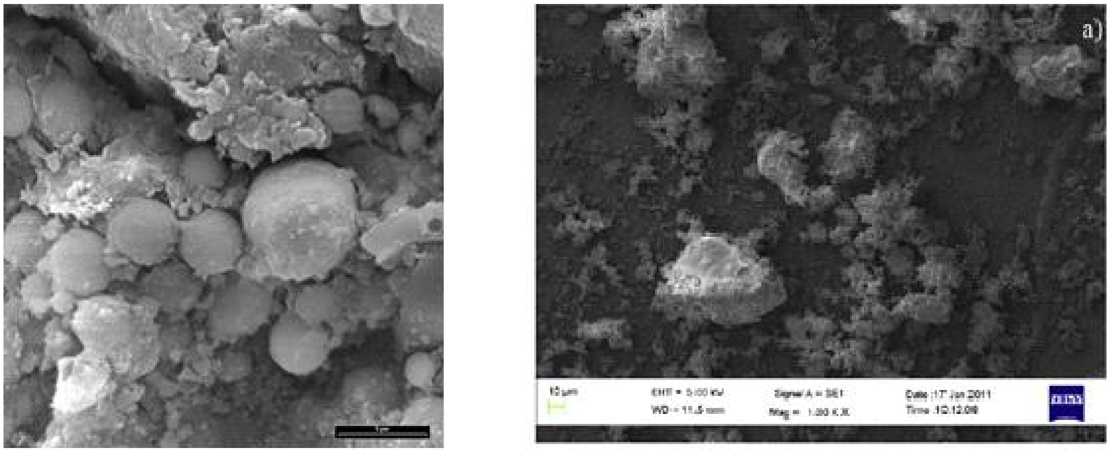


Fig. 15. Evolution of normalized static yield stress with resting time for mortars and concretes with coal bottom ash using HRWR= 0.4%.



a) b)

Fig. 16 . a) SEM micrographs showing the particles morphology of coal bottom ash. b) SEM micrographs showing the particles morphology of biomass ash (Maschio *et al*., 2011).

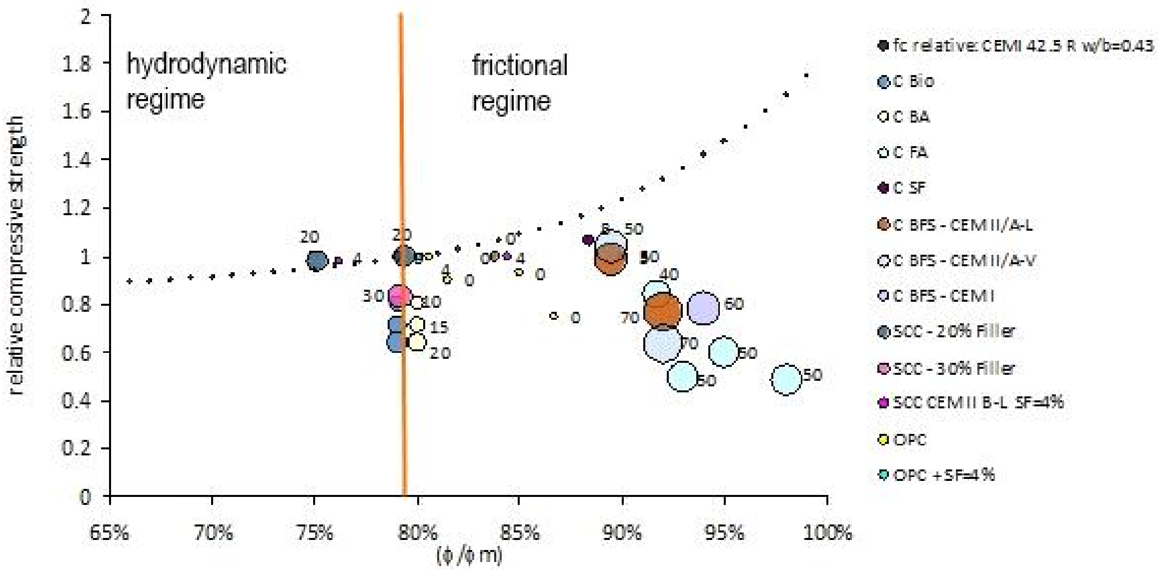


Fig. 17. Relative compressive strength as a function of the relative solid volume fraction for several concrete compositions (including the new ones). The legend presented near each bubble is the percentage used as cement replacement

showing the particles morphology of coal bottom ash and biomass ash, respectively.

Machio *et al*. (Maschio *et al*., 2011) analysed the rheological behaviour of biomass ash combustion as cement replacing components in mortars production. SEM analysis of powder particles morphology revealed that biomass ash contains mostly irregular large sized clusters of particles, their dimensions ranging from <10 to 100 μm (Fig. 18). Since in the results of the present work the addition of more HRWR seems to not affect the behaviour of M Bio, probably biomass ash here are still forming agglomerates which prevent the effectiveness of the superplasticizer.

The fresh and hardened state results mean that the microstructure of a first BA mortar or BA concrete layer becomes denser and the skeleton more resistant. However, this is a slow process and the penetration of the second layer becomes less complicated. A wider range of injection time or casting time is reached with coal bottom ash compositions when compared with the biomass ash and reference mortars and concrete composition tested. Besides that, a substantial improvement of the medium homogeneity may be obtained. Figs. 10-13 results already indicated that the incorporation of coal bottom ash in mortars and concretes seem to work as a filler and as a pozzolan, leading to the reduction of porosity values and to an increasing of strength and stiffness with time.The previous rheological results show that a huge modification in a concrete yield stress value does not mean an expressive change in concrete mechanical strength. In fact, an incorporation of biomass or coal bottom ash leads to the same compressive values at 28 days.

The results of normalized yield stress show that in most of compositions there is a proportion between mortar and the concrete from the same family. Accordingly, the yield stress of the suspensions (i.e. the concrete) is proportional to the yield stress of its suspending fluid (i.e. the constitutive cement paste). Thus, based on the results presented in this paper and in the results presented by other authors, the aggregate volume fraction and the maximum packing volume fraction were calculated for eleven different concrete compositions (see Fig. 17). Then, the relative compressive strength was calculated as a function of the relative solid volume fraction for each concrete. Those results are presented in Fig. 17. 6 new concretes can be added to Table 1 data: C BA / CBio, with an incorporation ratio (%) of Bio or BA ashes of 10, 15 and 20%. According to the previous results, if granular content is below the transition between frictional regime and hydrodynamic regime then the contribution of the aggregates to the yield stress of the mixture will be low, which is the case of CBio and CBA, leading to less compressive strength influence.

CONCLUSIONS

In the first part of this work, the authors analysed the evolution of compressive strength for several concretes with different compositions including several addition types. The aggregate volume fraction and the maximum packing volume fraction were calculated for eleven different concrete compositions. It was shown that the incorporation of biomass ash or coal bottom ash is probably optimized if they are used in a SCC formulations, where the relative compressive strength should decrease less in comparison to non-SCC concretes. More benefit is obtained in mortars and concretes with self-levelling behaviour by incorporating Biomass ash and Coal Bottom ash. The experimental program was developed based in this assumption.

One original aspect of the work is the use of yield stress normalization as a useful tool in rheological analysis. Finally, the consequences of biomass or coal bottom ash addition as cement substitution in mix design on the rheological and mechanical strengths of mortars and concretes were studied.

Based on the testing program, the following conclusions may be drawn:

- Coal bottom ash increase concrete/mortars workability, and their yield stress becomes at least 1.5 – 2 times smaller than the reference blend (M Ref or C Ref). However, the same does not happen with biomass ash compositions, where increasing their quantity decrease mortar and concrete workability.
- These concretes present low resistance to high pump speeds, namely a low plastic viscosity, making them particularly attractive for use in situations where there is a need for pumping concrete to a high altitude.
- The low resistance to high injection speeds also enable the use of BA mortars as a repair material in beams concrete jacketing, allowing an easy spread of mortar in the formwork.
- The presented results show that all BA mortars fulfil the compressive strength and stiffness requirements to be used as repair mortars, allowing the replacement of 15% or 20% of cement by an industrial waste.
- The decrease in mechanical strength for C BA at 28 days is not significant if more than 10% of BA is added. At 60 days there is an expressive strength increase of 1.15 to 1.20 times for the concretes with coal bottom ash, enhancing its pozzolanic effect.
- The concretes with biomass ash (CBio) do not present significant benefits when compared to CRef. However, the replacement of 10% of cement by biomass ash seems to lead to similar behaviour as CRef.
- The previous rheological results show that a huge modification in a concrete yield stress value does not mean an expressive change in concrete mechanical strength –those ashes lead to the same compressive values at 28 days.
- If granular content is below the transition between frictional regime and hydrodynamic regime then the contribution of the aggregates to the yield stress of the concrete mixture will be low, which is the case of CBio and CBA, leading to less compressive strength influence – the incorporation of those industrial by-products is optimised if the granular content of concretes are below the transition between frictional regime and hydrodynamic regime.

ACKNOWLEDGEMENTS

The authors recognize and thank all the contribution of engineers Bruno Miguel, Wilson Luís and Vítor Silva of ESTB/IPS on the tests carried out for the completion of the experimental part of the work herein presented.

REFERENCES

Canpolat, F., Yilmaz, K. Kose, M. M., Sumer, M. and Yurdusev, M.A. (2004). Use of zeolite, coal bottom ash and fly ash as replacement materials in cement production. Cement and Concrete Research, **34,** 731–736, 2004.

Cheriaf, M., Rocha, J. C. and Pera, J. (1999). Pozzolanic properties of pulverized coal combustion bottom ash. Cement and Concrete Research, **29(9),** 1387-1391.

Comparison of concrete rheometers: international tests at LCPC (Nantes, France) in October 2000, in: C.F. Ferraris, L.E. Brower (Eds.), National Institute of Standards and Technology Interagency Report (NISTIR), 6819, 2001.

Comparison of concrete rheometers: International tests at MB (Cleveland OH, USA) in May 2003, in: C.F. Ferraris, L.E. Brower (Eds.), National Institute of Standards and Technology Interagency Report (NISTIR), 7154, 2004.

Coussot, P., Proust, S. and Ancey, C., (1996). Rheological interpretation of deposits of yield stress fluids. J. Non-Newtonian Fluid Mech. **66,** 55–70.

Coutinho, A. S. and Gonçalves, A. (1994). Production and Properties of Concrete – Vol. III, LNEC, Lisbon (in portuguese)

de Larrard F. (1999). Concrete Mixture Proportioning, E & FN Spon, London, 1999.

Domone P. (1998). The slump flow test for high-workability concrete, Cem. Concr. Res. **28,** 177–182.

Flatt, R., Larosa, D. and Roussel, N. (2006) Linking yield stress measurements: Spread test versus Viskomat. Cem Concr Res 36: 99–109.

Geiker, M.R., Brandl, M., Thrane, L.N. and Nielsen L.F. (2002). On the effect of coarse aggregates fraction and shape on the rheological properties of self compacting concrete, Cem., Concr. Aggreg. **24 (1),** 3–6, 2002.

Khayat Omran, A. and Pavate, T. (2010). Inclined Plane Test to Evaluate Structural Build-up at Rest of Self-Consolidating Concrete, ACI Materials Journal, **107,** 515-522, ACI.

Khayat, K. and Omran, A. (2009). State-of-the-Art Review of Form Pressure Exerted by Self-Consolidating Concrete, Université de Sherbrooke, Canada.

Krieger, I.M. and Dougherty T.J. (1959). A mechanism for non-Newtonian flow in suspensions of rigid spheres, Trans. Soc. Rheol. **3,** 137–152.

Lothenbach, B. Scrivener, K. and Hooton, R.D. (2011) Supplementary cementitious materials. Cem Concr Resear; **41,** 1244-1256.

Marques, P.F. and Costa, A. (2010). Service life of RC structures: Carbonation induced corrosion. Prescriptive vs. performance-based methodologies, Constr Build Mater, **24(3),** 258-265.

Marques, P.F., Costa, A. and Lanata, F. (2012). Service life of RC structures: Chloride induced corrosion. Prescriptive vs performance-based methodologies. Materials and Structures, **45,** 277-296.

Maschio, S., Tonello, G., Piani, L. and Furlani, E., (2011). Fly and bottom ashes from biomass combustion as cement replacing components in mortars production: Rheological behaviour of the pastes and materials compression strength, Chemosphere, **85(4),** 666-671.

McNally, C. and Sheils, E. (2012). Probability-based assessment of the durability characteristics of concretes manufactured using CEM II and GGBS binders, Construction and Building Materials Volume 30, Pages 22–**29,** 2012.

Rajamma, R., Ball, R. J., Tarelho, L., Allen G., Labrincha, J. and Ferreira, V. (2009). Characterisation and use of biomass fly ash in cement-based materials, Journal of Hazardous Materials, **172(2-3),** 1049-1060.

Roussel N. (2007). Rheology of fresh concrete: from measurements to predictions of casting processes. Materials and Structures, **40,** 1001–1012.

Roussel N. (2006). Correlation between yield stress and slump: comparison between numerical simulations and concrete rheometers results. Mater Struct. **39(4),**501–509.

Roussel N., Staquet S., D'Aloia Schwarzentruber L., Le Roy R. and Toutlemonde F. (2007). SCC casting prediction for the realization of prototype VHPC-precambered composite beams, Mat. Struct. **40 (9),** 877–887.

Roussel N., Stefani C. and Le Roy R. (2005). From mini cone test to Abrams cone test: measurement of cement based materials yield stress using slump tests. Cem Concr Res. **35(5),** 817–822.

Senff, L. Barbetta, P., Repette, W., Hotza, D., Paiva, H., Ferreira, V. and Labrincha, J. (2009). Mortar composition defined according to rheometer and flow table tests using factorial designed experiments, Construction and Building Materials, **23,** 3107–3111.

Sideris, K., Anagnostopoulos, N. (2013). Durability of normal strength self-compacting concretes and their impact on service life of reinforced concrete structures, Construction and Building Materials, **41,** 491-497.

Torgal, F., Shasavandi, A. and Salali, S. (2013). Eco-Efficient concrete Using Industrial Wastes: A Review. Materials Science Forum, Trans Tech Publications, 730-732,581-586.

Wang S. Z., Llamazos, E., Baxter, L. and Fonseca, F. (2008). Durability of biomass fly ash concrete: Freezing and thawing and rapid chloride permeability tests. Fuel, **87(3),** 359-364.

Wang, S. Z., Miller, A., Llamazos, E., Fonseca, F. and Baxter, L. (2008). Biomass fly ash in concrete: Mixture proportioning and mechanical properties, Fuel, **87(3),** 365-371.

Yammine, J., Chaouche, M., Guerinet, M. and Roussel, N. (2008). From ordinary rheology concrete to self compacting concrete: A transition between frictional and hydrodynamic interactions, Cement and Concrete Research, **38,** 890–896.