OPTIMISATION DESIGN AND ASSESSMENT OF ARCHITECTONIC AND ECO-FRIENDLY HPC

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Abstract
High-performance concrete (HPC) is currently among the most technologically advanced concrete types. One exciting application of HPC is thin architectonic elements. However, from a materials point of view, some issues need to be addressed, namely regarding sustainability. Portland cement and supplementary cementitious materials (SCM) such as slag, fly ash, silica fume and limestone are important constituents in HPC mixture design. However, for architectonic HPC, white cement is generally employed. The partial replacement of white Portland cement by white coloured SCM is beneficial from an economic, technical and environmental point of view. In Portugal and many other countries, white SCM is scarce. Using locally available SCM reduces costs and CO2 emissions allocated to concrete production, particularly valorising local industrial waste or by-products, such as glass powder. This solution contributes in an integrated way to achieve more sustainable and circular concretes. The current work presents the optimisation mixture design and assessment of architectonic and more eco-friendly HPC formulated with considerable amounts of industrial waste. An integrative evaluation of engineering properties, such mechanical strength, resistivity, whiteness control and an ecological parameter, were considered.

1. INTRODUCTION

HPC is a family of advanced cementitious composites featuring self-compacting ability, superior mechanical properties, durability, and a polished aesthetic appearance [1]. HPC has been employed in building facades, cladding systems, urban furniture, and architectural elements due to its versatility and capability to accommodate intricate geometric shapes [2].

When applied in building facades, the colour of HPC is an important requirement for aesthetic property. Nevertheless, with the growing need for sustainable buildings, the colour of building façades has become a relevant factor in energy consumption and durability. Façades painted with darker colours absorb more heat than lighter ones, resulting in higher temperatures [3]. This temperature difference can cause a significant rate of degradation in coatings, which is dependent on the colour of the coating. The agents that cause degradation include solar radiation, temperature and relative humidity fluctuations, and the effects of rain. Such agents produce undesirable effects such as colour changes, staining, and cracking [4].

White Portland cement, commonly used in architectural concrete, is characterised by lower iron and alkali contents and higher free lime content than conventional Portland cement. White cement is usually finner (if compared to an equivalent class of traditional Portland cement) because greater fineness increases whiteness, providing shorter setting times and higher mechanical strength at early ages, higher heat of hydration and shrinkage. These particularities of white cement should not negatively affect the final product performance, requiring an appropriate selection and combination of constituent materials in the mixture design studies. One of the effective options to reduce the risks associated with the use of white cement, particularly in high dosages, as in HPC, is the partial replacement of cement by supplementary cementitious materials.

The current work was devoted to developing an eco-friendlier white HPC using locally available raw materials, namely a ternary blend of white cement, limestone filler and waste glass powder (GP). The HPC sustainability (at the material level) was pursued via high dosages of cement replacement. As such, the Design of Experiments (DoE) approach was adopted to model the relationships between the main design variables (mix-proportion ratios) and relevant response variables (HPC properties).

2. MATERIALS AND METHODOLOGY

2.1. RAW MATERIALS

The HPC was designed using a ternary blend including Portland cement CEM II A-L 52.5N (according to EN 197-1), limestone filler and waste glass powder. The aggregate was natural siliceous sand with a maximum particle size of 1 mm. To reach self-compacting mixtures, a polycarboxylate-type high-water reducer was used. The waste glass was obtained from a recycling glass industry in Portugal. The cullet particles were then reduced to a particle-size glass similar to Portland cement. The reduction was performed in a dry state with a ball mill.

2.2. EXPERIMENTAL DESIGN

A central composite design (CCD) was adopted, including 4 central points, 16 factorial points and 10 axial points. The independent variables (mixture parameters) identified as relevant in other studies [5]–[7] were adopted in the current work and presented in Table 1, namely, water-to-powder volume ratio (Vw/Vp), water-to-cement weight ratio (w/c), superplasticiser to powder weight ratio (sp/p) and waste glass powder to cement replacement weight ratio (GP/c). The output properties (response variables) were the compressive strength (Rc,28d [MPa]), the electrical resistivity – (Resist,28d [Ωm]), GWP (kg CO_2/m^3) and whiteness (W [%]).

The compressive strength was assessed according to NP EN 196-1. The two-electrode method measured the electrical resistivity on prismatic specimens (40 × 40 × 160 mm3) (see Figure 1). At 28 days, the whiteness was evaluated according to the Portuguese specification LNEC E 357. As the white standard, magnesium oxide with high purity was used, corresponding to a reflectance of 100% in all visible spectrum wavelengths. The directional luminous reflectance factor (G) value was considered equal to 100, and the tristimulus X, Y and Z with values of 98.00, 100.00 and 118.1, respectively.

Table 1. Independent variables identification and ranges (correspondence between coded and real values).

	Actual mixture parameters			
Coded mixtures parameters	A=Vw/Vp	B=w/c	C=Sp/p (%)	D=Gp/c
-2	0.360	0.230	1.660	0.100
-1	0.380	0.250	1.680	0.175
0	0.400	0.270	1.700	0.250
1	0.420	0.290	1.720	0.325
2	0.440	0.310	1.740	0.400

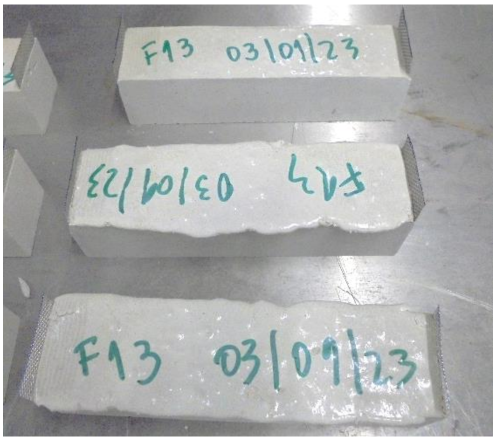


Figure 1. Specimens with embodied stainless-steel mesh for electrical resistivity assessment.

In the current work, global warming potential (GWP) was used as an environmental indicator of designed mixtures on a volumetric basis, i.e., the sum of the embodied carbon of each constituent raw material, presented in Table [8] [9], to produce 1 m3 of each HPC mixture in the CCD. According to the criteria defined in the European Union directive, the glass powder was considered waste; thus, no GWP allocation was performed.

Table 2 - GWP for each constituent material employed to produce HPC.

Material	GWP (Kg CO_2/kg)
Cement	0.691
Limestone filler	0.01702
Glass powder	0
Natural Sand	0.00106
Water	0.000318
Superplasticizer	0.944

3. RESULTS AND DISCUSSION

3.1. EXPERIMENTAL RESULTS SUMMARY

Table 3 presents the statistical summary description of experimental results for the response variables Rc,28d (MPa), Resist,28d (Ωm), GWP and W (%). The electrical resistivity results varied between 69.63 and 178.80 Ωm. The compressive strength results presented a narrow variation between 87.26 and 101.99 MPa, typically observed on high-performance cement-based materials. The results obtained seem to be adequate for HPC. Regarding the whiteness, a variation of 13% was observed among all CD mixtures, in which the maximum value was 56 and minimum 47. According to [10], white/light colours present a solar reflectance higher than 0.7, impacting the thermal behaviour of façades by increasing the reflected energy [11]. The GWP was relatively high, which is common for HPC when considering only material levels impacts. A maximum value of 549 KgCO_2/m^3 was obtained.

Table 3. Statistical description of the results obtained in the CCD.

Statistics	**Rc,28d (MPa)**	**Resist,28d (Ωm)**	**Whiteness (%)**	**GWP (Kg CO_2/m^3)**
Maximum	101,99	178,80	56,47	549,23
Minimum	87,26	69,63	30,97	417,67
Average	94,05	102,49	46,97	476,60
Std. Dev.	3,87	29,02	6,19	32,30
coef var (%)	4,12	28,32	13,18	6,78

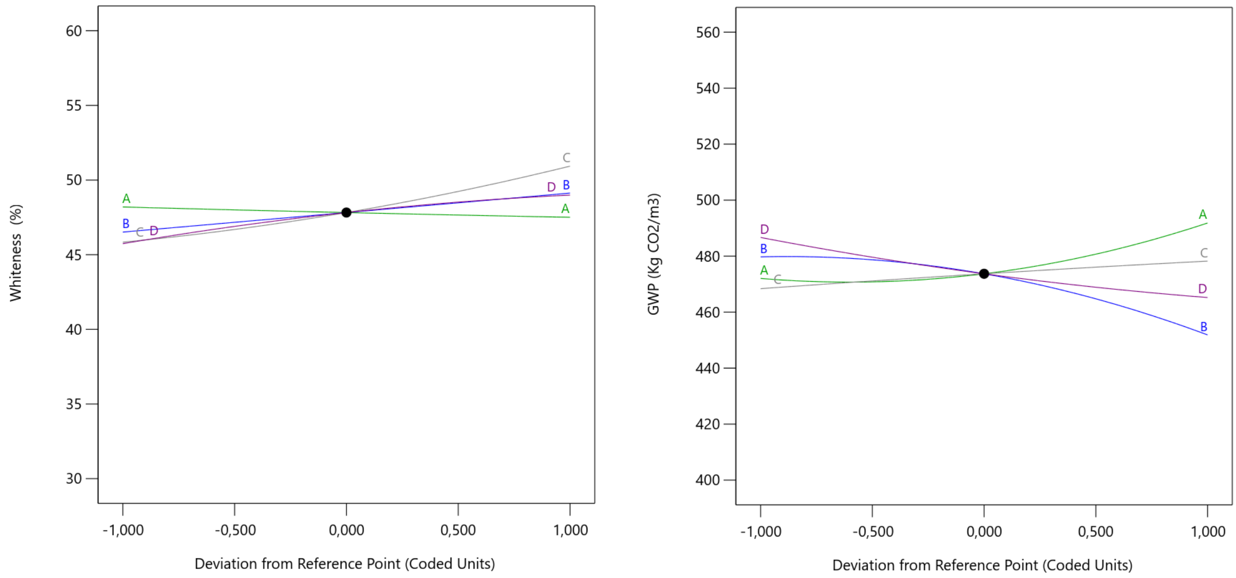
3.2. REGRESSION MODELS AND MOST SIGNIFICANT EFFECTS

The model fitting was performed through multilinear regression analysis and analysis of variance (ANOVA), followed by the validation of the models through the analysis of the residuals looking for trends, evidence of autocorrelation or "outliers". A more detailed description of these procedures can be found in [5]. The models obtained are presented in Table 4. As can be perceived, Vw/Vp significatively influences all responses. The most significant contributions to the resistivity at 28 days are GP/c (positive contribution) and w/c (negative contribution). Concerning compressive strength, as expected, water content has a significant effect (factors Vw/Vp and w/c).

Table 4 - Fitted models for response variables Resist,28d (Ωm) and Rc,28d (MPa).

	Resist,28d (Ωm)	**Rc,28d (MPa)**
Intercept	-169,7	118,0
Vw/Vp	359,6	53,42
w/c	368,7	-168,0
GP/c	2128,1	
Vw/Vp * GP/c	-2660,0	
w/c * GP/c	-4218,8	
$(GP/c)^2$	793,6	
R^2/R^2adjust	0,958/0,918	0,745/0,725

The whiteness and GWP indicators are plotted in Figure 2 by changing only one design variable over its range while holding all other design variables constant. The level of slope or curvature in mixture parameters indicates the sensitivity of these factors when a mixture parameters change and the others remain the same. As can be seen, the whiteness slightly increases, by order, with factors C, B and D (Sp/p, w/c and GP/c). The GWP indicates sensitivity to changes in w/c and GP/c, which was expected since increasing those mixture parameters, decreases the cement content. Clearly, the w/c level is the most influencing parameter on the final GWP value. By increasing the factor A (Vw/Vp) the GWP increases.



a) b)

Figure 2. Influence of mixture parameter on a) Whiteness and b) GWP.

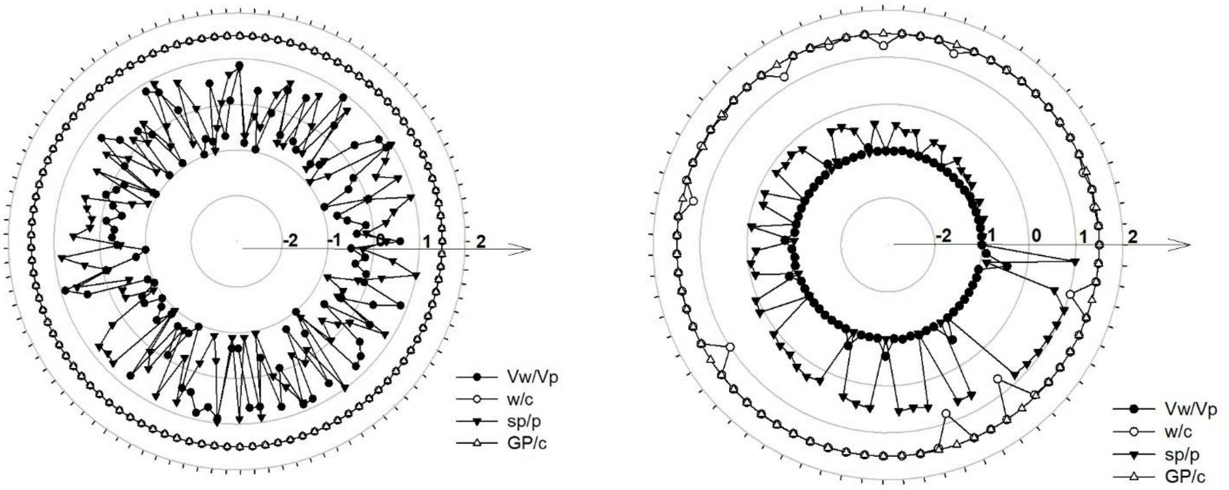
3.3. HPC OPTIMISATION

The HPC mixtures were optimised using the response surface of the models presented in Table 3. Table 4 presents two different optimisation scenarios implemented. In brief, in scenario A aimed to obtain HPC with lower embodied CO2 (at the material level) by increasing w/c and Gp/p; and scenario B aiming to reproduce scenario A but also increased the resistivity of HPC. It must be stressed that the distance to the centre of the CCD plan should not exceed 2 by far (region of the original data) because the fitted models may no longer predict reasonably outside the CCD region. Thus, in scenarios A and B, mixture parameters Vw/Vp and sp/p were kept between (-1;1) and w/c and GP/c in the range (-1.5;1.5).

Table 1 - Optimisation criteria (design variables in coded values).

	Scenario A	Scenario B
Vw/Vp	[-1;1]	[-1;1]
w/c	maximise [-1.5;1.5]	maximise [-1.5;1.5]
Sp/p	[-1;1]	[-1;1]
GP/c	maximise [-1.5;1.5]	maximise [-1.5;1.5]
Resist,28 (Ω.m)	None	maximise
Rc,28d (MPa)	None	None

The mixture design obtained for the above optimisation criteria is presented in the radar plot of Figure 3 in coded values (see Table 1 for correspondence between coded and real values). Each radial segment represents one of the optimised solutions, and over this segment, a dot is plotted for each mixture variable using the corresponding marker. The interaction diagrams of the type presented in Figure 3 show a more global picture of the solutions highlighting other features of the optimisation since they enable one: (a) to rapidly distinguish which of the constituent materials combine well, in the sense that they favour the optimisation criteria established; (b) to distinguish regions where the solutions get very close to the circular boundaries corresponding to levels −2 and +2, indicating that the limits of the factorial plan have been attained and one has depleted the set of solutions; (c) to identify trends in the design of HPC. In Scenario A, 100 HPC mixtures were found with desirability 1, and optimal solutions come with an increase in the factor GP/c (close to 1.5 in coded value) and an increase the factor w/c (close to -1.5 coded value), while Vw/Vp and sp/p varied between -1 and 1. In scenario B, the desirability of 1 was not reached, being a maximum desirability of 0.853. In Figure3-b, only solutions with desirability higher than 0.80 are depicted. In this case, optimal solutions come with an increase in the factor GP/c (close to 1.5 in coded value) and an increase the factor w/c (close to -1.5 coded value) but with some exceptions, and Vw/Vp equal to -1 (coded value) and sp/p with variations between -1 and 1 (coded values).



a) Scenario A b) Scenario B

Figure 3. Range of optimal solutions obtained for scenarios A and B of Table 4.

4. CONCLUSIONS

Based on the presented results, the following conclusions can be drawn:

- HPC may contain an increasing number of constituents and several performance requirements. Thus, it is critical to use a systematic approach to identify optimal mixes given a set of performance constraints at both engineering and ecological levels.
- Quadratic models provide an adequate representation of each HPC property over the region of interest (resistivity and compressive strength) and can be used to identify optimal HPC mixes;
- An increase of GP/c while maintaining w/c (or a decrease of Vw/Vp) strongly influences the resistivity of HPC more than the influence of w/c;
- The GWP is mostly dependent on cement dosage,as such, the increase of w/c and GP/c, which implies the decrease of cement according to the formulation used in the current work, is a simple way to reduce the ecological footprint of HPC;
- It was shown that ground glass could be successfully applied in HPC, as a high-volume cement replacement material (up to 40%), thus widening the types of SCM available and reducing CO2 emissions by using less cement.

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