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# Porosity and strength of PFA/SF/OPC ternary blended paste

M.I. Khan, C.J. Lynsdale*, P. Waldron

*Centre for Cement and Concrete, Department of Civil and Structural Engineering, University of Sheffield, Sir Frederick Mapping Building, Mappin Street, Sheffield S1 3JD, UK*

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**Abstract**

The results presented in this paper form part of an investigation into the optimisation of a ternary blended cementitious system based on ordinary Portland cement (OPC)/pulverised fuel ash (PFA)/silica fume (SF) for the development of high-performance concrete. Cement pastes covering a wide range of PFA/SF blending proportions were investigated. Compressive strength and porosity at the ages of 7, 28, and 90 days for cement paste specimens containing 0%, 15%, 20%, 25%, 30%, 35%, 40% and 45% PFA along with 0%, 5%, 10% and 15% SF as partial cement replacement at a water–binder ratio of 0.30 were investigated. A statistical approach was used which permitted the calculation of the isoresponse curves for the parameters under study over the experimental domain and the optimisation of their effect. 

*Keywords:* Blended cement; High-performance concrete; PFA; Physical properties; Silica fume

## 1. Introduction

Concrete is used as a construction material in hostile environments in structures such as seafloor tunnels, offshore piers and platforms, highway bridges, sewage pipes, and containment structures for solid and liquid wastes containing toxic chemicals and radioactive elements. The requirements for acceptable durability performance in such conditions go beyond those achievable with ordinary cements. As a result, the blending of ordinary Portland cement (OPC) with pozzolanic materials has become an increasingly accepted practice in such structures.

Numerous publications [1,2] reporting improved rheology and cohesiveness, lower heat of hydration, lower permeability and higher resistance to chemical attack resulting from the use of different mineral admixtures have emerged over the years. However, individual pozzolanic materials normally have limitations and some have contrasting influences on properties of concrete. For example, partial replacement with pulverised fuel ash (PFA) normally results in lower early-strength but enhanced workability for a given water–binder ratio. On the other hand, silica fume (SF), with its finer particle size compared to PFA, results in higher reactivity than for PFA but with a downturn in workability as a result of the higher specific surface area. In order to derive the maximum short-term and long-term benefits from the use of these materials in high-performance concrete, ternary blends exploiting the potential synergy between these materials may be necessary. This possibility has been successfully demonstrated in the past [3,4].

At present, the information pertaining to these ternary blended systems, which is pertinent to their practical use, is scarce. To facilitate the standard specifications and better understanding of the behaviour of ternary blended cement, greater efforts are needed to transfer such technology, so that rapid implementation can occur.

The results presented in this paper form part of an investigation into the optimisation of a ternary blend based on OPC/PFA/SF for the development of high-performance concrete [5]. The results presented here are for paste systems, which in a future publication will be expanded to concrete systems.

## 2. Experimental details

### 2.1. Materials

OPC, conforming to the requirements of BS12: 1991, and PFA, complying with the requirements of BS3892:

* Corresponding author. Fax: +44-114-222-5700.
*E-mail address*: c.lynsdale@sheffield.ac.uk (C.J. Lynsdale).

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Part 1: 1993, were used in this investigation. SF was obtained in slurry form as a 50:50 solid-to-water ratio by weight. A 40% solids aqueous solution of sulphonated naphthalene formaldehyde condensate superplasticiser (HRWR) was used.

### 2.2. Blend proportions

PFA was used as an OPC replacement over a wide range: 0%, 15%, 20%, 25%, 30%, 35%, 40% and 45% (by weight). SF was incorporated in these blends at OPC replacement levels of 0%, 5%, 10%, and 15% (by weight). The total number of mixes investigated was 32. A water-to-binder (w/b) ratio of 0.30 was used throughout. The consistency of paste mixes was maintained nominally constant through the use of a superplasticiser. It is worthwhile to mention here that the water contents of the superplasticiser and SF slurry were taken into account when calculating the total water content of paste.

It was observed that the paste without SF maintained the required consistency without the need for a superplasticiser. The superplasticiser dosage required for the same nominal consistency was observed to increase with the increase in SF content, as expected. It was also noted that the ternary blended paste containing 20–25% PFA required higher superplasticiser dosage than paste containing 30–40% PFA for similar consistency.

### 2.3. Mixing procedure

Mixing was done in a 2-litre capacity *Hobart* mixer. The flow behaviour of SF paste was found to be greatly influenced by the mixing procedure. Therefore, a number of mixing procedures were examined in order to select one that would maximise the dispersion of the SF particles. The following procedure was found to be most effective.

1. PFA and OPC were dry-mixed for 30 s with the mixer operating at *medium* speed setting.
2. Half of the mixing water was added (pre-mixed with superplasticiser) during the next 30 s of mixing.
3. SF slurry was then added during the next 30 s of mixing.
4. The remainder of the mixing water was added.
5. Mixing was continued for a further 90 s.

The mixer was then stopped and the paste was scraped from the sides of bowl and hand-mixed before mixing at the *high* speed setting for 2 min.

### 2.4. Casting and curing

For the measurements of compressive strength and porosity, 50-mm cubes were cast. All specimens were cast and compacted in two layers on a vibrating table. After casting, the specimens were covered under damp hessain and polyethylene sheets. The samples were demoulded the following day and then kept in a mist room at 20±2°C, 95±5% RH for curing prior to testing.

## 3. Testing procedure

### 3.1. Flow (consistency)

The flow of the paste was measured using a flow table normally used for mortar in accordance with BS4551: 1980. The flow of all paste mixes was maintained at 205±10 mm.

### 3.2. Compressive strength and porosity

Compressive strength and porosity were measured at the ages of 7, 28 and 90 days. The compressive strength was determined in accordance with BS1881: Part 116: 1983. Vacuum saturation in accordance with RILEM Recommendation CPC-11.3: 1984 was used for measuring the water-permeable porosity. The measurements for compressive strength and porosity were taken for triplicate samples and the mean was reported as result.

The influence of PFA and SF contents on compressive strength and porosity at the ages of 7, 28 and 90 days were analysed statistically using the *Minitab* statistical software package [6]. The statistical method used highlights the significance of the effect of the experimental variables and their interactions and has predictive capability for the response of other experimental values located within the experimental domain. This permitted the calculation of the isoresponse curves from the parameters under study over the experimental domain and the optimisation of their effects.

A response variable $y$ is measured at combinations of values of two-factor variables $x_1$ and $x_2$. The quadratic response-surface model for this variable is as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2$$

where: $y$ is the observation of the responsive variable, $x_1$ and $x_2$ are the factor variables for $y$, $\beta_1$, $\beta_2$, ... , $\beta_{12}$ are the coefficients of the model.

In the present investigation, the two experimental variables were the proportions of PFA ($x_1$) and SF ($x_2$) as partial cement replacements. The responses of the experiment were compressive strength, $f_{cu}$, and porosity, $p$ (as represented by $y$ in the equation above), at the age of 7, 28 and 90 days.

## 4. Results and discussions

### 4.1. Compressive strength

The models for compressive strength, based on quadratic response-surface, at the ages 7, 28 and 90 days are

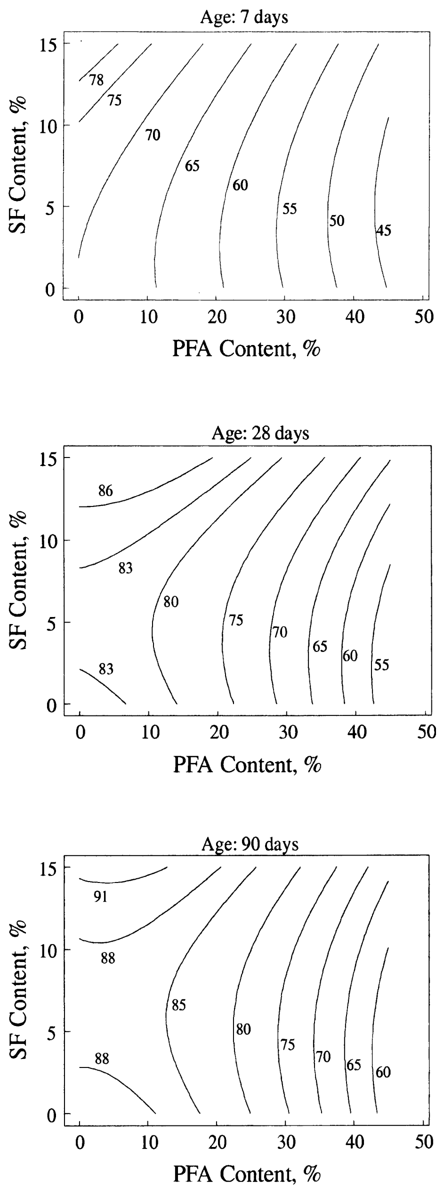


Fig. 1. Isoresponse curves for compressive strength for various ages.

as follows. Terms that were found to be statistically not significant have been taken out of the equations below:

$$f_{cu7} = 69.90 - 0.390x_1 - 0.004x_1^2 + 0.053x_2^2 - 0.011x_1x_2, \; R^2 = 0.93$$

$$f_{cu28} = 84.45 - 0.128x_1 - 0.852x_2 - 0.013x_1^2 + 0.082x_2^2 + 0.012x_1x_2, \; R^2 = 0.95$$

$$f_{cu90} = 90.15 - 0.962x_2 - 0.016x_1^2 - 0.072x_2^2 + 0.010x_1x_2, \; R^2 = 0.90$$

where: $f_{cu7}$, $f_{cu28}$, and $f_{cu90}$ are the compressive strengths at 7, 28 and 90 days, respectively, $x_1$ is the amount of PFA as partial cement replacement (%), $x_2$ is the amount of SF as partial cement replacement (%), $R^2$ is the coefficient of determination and measures the variation in the response that is attributed to the model rather than to the random error.

Fig. 1 plots the isoresponse curves corresponding to 7, 28 and 90 days compressive strength. These figures show the change in compressive strength for all ages as caused by the effect and interaction of the two independent variables, which are the PFA and SF contents. The predicted values agree very closely with the experimental values as shown in Fig. 3.

From Fig. 1, it can be seen that the compressive strength decreases with an increase in PFA content for a particular SF content, for all ages tested. On the other hand, increasing the SF content for a particular PFA content above 5% replacement level, results in an increase in compressive strength. It is evident that up to 5% SF

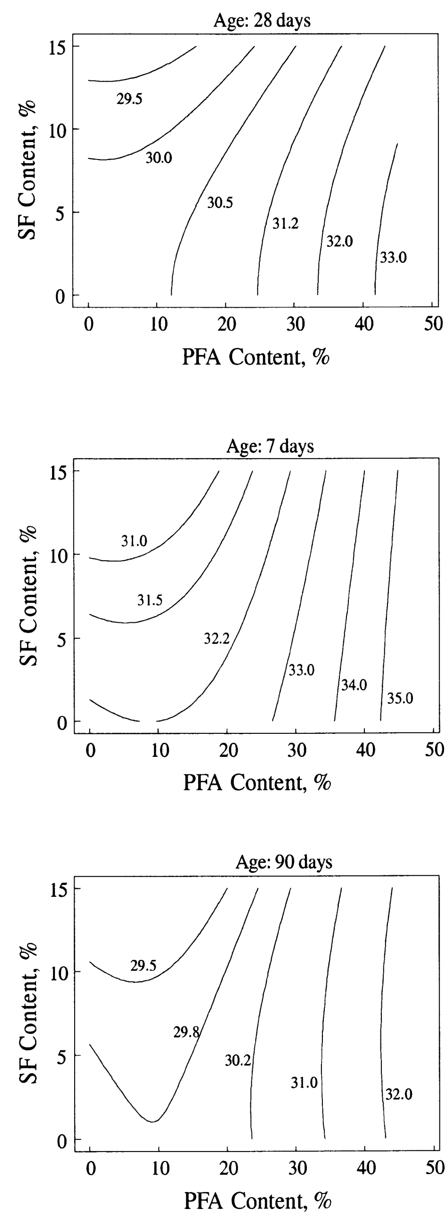


Fig. 2. Isoresponse curves for porosity for various ages.

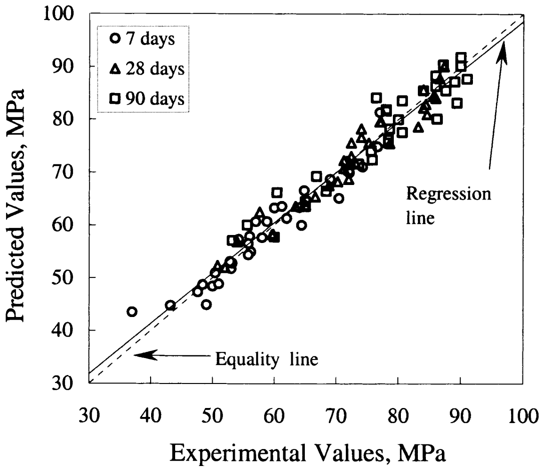


Fig. 3. Relationship between predicted values and experimental values of compressive strength.

incorporation in ternary blended systems has no beneficial effect in increasing compressive strength over those of OPC or OPC/PFA pastes for all ages investigated. For example, cement paste with a 0% SF+18% PFA combination exhibits 62 MPa at 7 days, similar to that of 5% SF+18% PFA paste; while paste mixtures containing 10% SF+18% PFA and 15% SF+18% PFA exhibited 65 and 70 MPa 7-day strengths, respectively. The observed increase in early-age strength as a result of the incorporation of SF is probably related to its high reactivity as demonstrated by earlier researchers [7,8].

At the ages of 28 and 90 days (Fig. 1), the response curves have similar patterns, indicating a similar type of effect caused by PFA and SF for these two ages. Fig. 1 also exhibits only a small increase in strength between 28 and 90 days. It is also evident that at 90 days and for PFA contents lower than 12%, the incorporation of SF by up to 15% did not seem to affect the compressive strength appreciably. For example, cement paste containing 0% SF+12% PFA and cement paste made with 12% SF+12% PFA displayed the same strength of 88 MPa.

It has been demonstrated that SF increases the strength of cement paste [9]. However, it is also reported that SF is more effective in concrete than in paste [10]. This increase in concrete strength containing SF is attributed to an aggregate–paste bond improvement, which is associated with the formation of a less porous transition zone in SF concrete [11]. This investigation therefore, has been extended to concrete and the results will be published in due course.

### 4.2. Porosity

The models for porosity, based on the quadratic response-surface, at the ages 7, 28 and 90 days are as follows:

$$p_7 = 32.373 - 0.042x_1 - 0.129x_2 + 0.002x_1^2 + 0.003x_1x_2,\ R^2 = 0.93$$

$$p_{28} = 30.328 + 0.002x_1^2 - 0.005x_2^2,\ R^2 = 0.91$$

$$p_{90} = 29.977 - 0.036x_1 - 0.015x_2 + 0.002x_1^2 - 0.003x_2^2 + 0.001x_1x_2,\ R^2 = 0.97$$

where: $p_7$, $p_{28}$, and $p_{90}$ are the porosity values at 7, 28, and 90 days, respectively; $x_1$ is the amount of PFA as partial cement replacement (%); $x_2$ is the amount of SF as partial cement replacement (%).

The isoresponse curves for 7-, 28- and 90-day porosity, as a function of PFA and SF proportions, are presented in Fig. 2. These figures show the changes in porosity for all ages caused by the effect and interaction of the two independent variables, PFA and SF. A good correlation between the experimental values and those predicted from the above equations is achieved (Fig. 4).

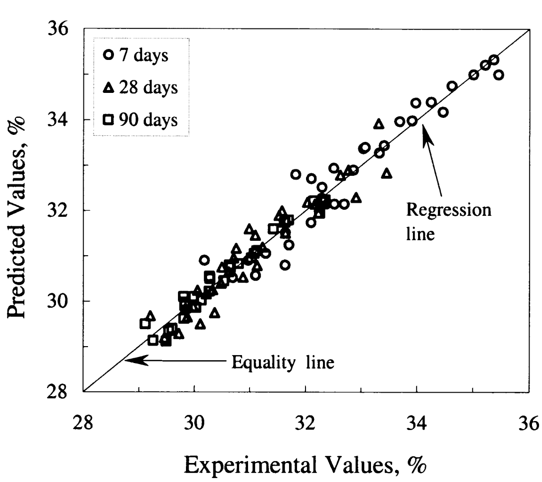


Fig. 4. Relationship between predicted values and experimental values of porosity.

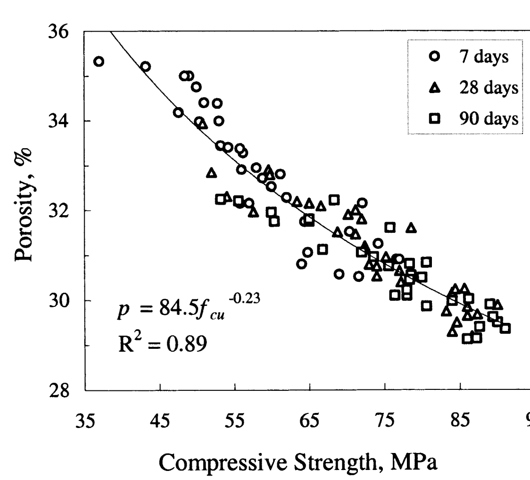


Fig. 5. Relationship between compressive strength and porosity.

The 7-day porosity of paste (Fig. 1) increased with an increase in PFA content. The increase being greater as the PFA content is increased beyond 15%. It is worth noting that porosity values changed over a narrow range. When all ages are considered, this range stretched from 29.5% to 35.5%. It is important to appreciate that this range of porosity values corresponded to compressive strengths over the range 35 to 88 MPa (Fig. 5).

The incorporation of SF resulted in a slight reduction in porosity, being most noticeable at early ages and for PFA contents lower than 15%. At 90 days and for PFA contents above 15%, the response curves are almost vertical suggesting that changing the SF content has no effect on porosity.

## 5. Conclusions

Increase in PFA content was associated with reduction in strength and increase in porosity in comparison with the OPC control paste for all ages investigated.

As SF was incorporated as a cement replacement alone, early-age strength was slightly increased and porosity was slightly reduced. However, as PFA was introduced in the ternary blended systems, the strength was reduced and porosity increased.

Although none of the ternary blended systems achieved the strength and porosity of the OPC control, these systems are viable when economical and environmental benefits are sought given the level of performance achieved.

A relationship between strength and porosity has been established for these systems governing all ages investigated.

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