JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT
2009
15(2): 131–135

CONSISTENCY OF FLY ASH AND METAKAOLIN CONCRETE

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Received 24 July 2008, accepted 7 Apr 2009

Abstract. As high-performance Portland cement (PC), fly ash (FA) and metakaolin (MK) concrete have been developed in wide applications, it has growing interest in optimizing and predicting consistency of fresh PC-FA-MK concrete for efficient and practical design and construction. This paper presents statistical models for predicting the consistency of concrete incorporating PC, FA and MK from the experimental results of standard consistency tests. They reflect the effect of variations of pozzolanic replacement materials including FA and MK at graduated replacement levels of up to 40% and 15%, respectively. The predictions produced are compared with the experimental results of consistency of concrete blends. Models show that they can be used to predict the consistency parameters including slump, compacting factor and Vebe time with a good degree of accuracy in a wide range of FA-MK blends. Design guidelines for evaluating consistency parameters are tentatively recommended along with their confidence intervals for prediction limits at 5% significance levels.

Keywords: concrete consistency, prediction, regression models, portland cement, fly ash, metakaolin.

1. Introduction

The world production of cement has greatly increased since 1990. Although concrete has many advantages over other construction materials including low cost, adaptability and applicability under many conditions, use and production of cement and concrete has increasingly become a major cause of global ecological problems with special reference to the over exploitation of non-renewable natural resources due to high-temperature production processes, fossil fuels combustion and extraction of raw materials (Damtoft, Lukasik 2008; Berry, Malhorta 1990). Asif, Muneer (2007) studied 8 construction materials for a dwelling in Scotland. These materials were: timber, concrete, glass, aluminium, slate, ceramics tiles, plasterboard, damp course and mortar. The study concluded that the material used in the house with the highest level of embodied energy was concrete, at 61%. Increasing use of by-products, such as FA (British Standards Institution 1993 and 1985; Concrete Society 1991; Guemandi *et al.* 2008), to partially replace Portland cement in concrete not only reduces the amount of cement used, hence reducing the emission of CO_2 and conserving existing resources (Davies, Kitchener 1996; Kon, Poon 2008), but significantly enhances the properties of concrete (Dhir *et al*. 1988; Dhir *et al.* 1993; Curcio *et al.* 1998; Chia, Zhang 2004; Gribniak *et al.* 2008). Inclusion of FA in concrete greatly improves consistency (Wild *et al.* 1996). Research work done on metakaolin (Curcio *et al.* 1998) has shown that the partial replacement of PC with MK in concrete significantly affects consistency and early strength (Banfil, Frias 2007; Kostuch *et al.* 2006). However, metakaolin unlike FA results, with increasing replacement levels of metakaolin, increases water demand (Bai *et al.* 2008) due to its high chemical activity and high specific surface. The investigation into optimising the contributory effects of FA and MK on concrete properties by introducing them in combination has been carried by Bai *et al.* (2009). The research results on consistency of PC-FA-MK blends have shown that loss of consistency due to the presence of MK can be compensated for by the incorporation of FA. The degree of restoration of consistency, provided by FA, is influenced significantly by the cement replacement level.

Comprehensive experimental consistency data on PC-FA-MK blends (Bai *et al.* 2009) was largely understood on a comparative basis. It would be more useful if statistical trends can be extrapolated to develop reliable predictive models. Such models are very important (Brower, Ferraris 2005) as they help designers to select FA-MK combinations in performance terms and can be also used as a tool in laboratory to select optimal combinations for further research work on properties, such as strength development and durability.

2. Data source and scope

The data used for developing the consistency prediction models in this paper were extracted from research work. The data were obtained by standard experimental consis-

ISSN 1392–3730 print / ISSN 1822–3605 online
DOI: 10.3846/1392-3730.2009.15.131-135

tency tests (BS 1881: Part 102: 1983; BS 1881: Part 103: 1983; BS 1881: Part 104: 1983). They represent a wide range of mix proportions and materials. The concrete mixes selected for developing a predictive model are those with a water binder ratio of 0.5 and range from grade 25 to grade 80 N/mm^2. They incorporate variations of pozzolanic replacement materials including fly ash and metakaolin at graduated replacement levels up to 40% and 15%, respectively.

3. Consistency models of PC-FA-MK concrete

3.1. Parameters affecting consistency of PC-FA-MK concrete

The data obtained for the consistency of PC-FA-MK blends as binder with water binder ratio 0.5 confirmed that the major contributory factor to the concrete mix consistency was the type and relative amounts of the binder constituents used. The consistency was found to be most closely dependent upon the FA and MK contents (%) and therefore these parameters are selected as independent variables for modelling the consistency models.

3.2. Models for predicting slump

It would be desirable for the slump to be predicted by reliable models. A close examination of the slump data for PC-FA-MK concrete with w/b ratio 0.5 shows that slump is essentially dependent on replacement levels of both FA and MK. To include a practical range of cementious materials, analysis was carried out on data taken from concrete made with a binder consisting of Portland cement (PC) combined with FA ranging from 0%–40% and MK varying from 0%–15%. Due to variation of the slump values with different FA and MK replacement levels, for increased additional accuracy a regression analysis was performed and best-fit formula obtained for PC-MK blends and FA-MK blends at different total relacement levels. The general slump equation adopted was of the form SLUMP = $\alpha_0+\alpha_1x+\alpha_2x^2+\alpha_3x^3$, where α_i is coefficients for particular replacement level and x is percentage of replacement by pozzola (FA or MK):

for PC-MK concrete (without FA)

$$SLUMP = \alpha_0 + \alpha_1 M + \alpha_2 M^2 + \alpha_3 M^3 , \qquad (1)$$

for FA-MK concrete

$$SLUMP = \alpha_0 + \alpha_1 P + \alpha_2 P^2 + \alpha_3 P^3 , \qquad (2)$$

where α_i are regression constants, $M = MK$ content (%), $P = FA$ content (%).

Parameters α_i are primarily dependent on blend type and total replacement level. Based on the available slump data, after comprehensive regression analysis and significance testing, the best-fit coefficients of α_i were found and are given in Table 1.

The multivariate regression output representing the summary of best-fitting models to the data for slump prediction is given in Table 2. From Table 2, the values of R^2 are all greater than 0.99 and show that above 99% of the variation in the slump is accounted for by the model. Since the R^2 can be at most 1, the values of R^2 in Table 2 confirm a good fit between the sample regression lines and the data. The F values support the findings as being statistically significant.

Values of slump of concrete with FA and MK were calculated using the proposed models and compared with actual experimental data. Fig. 1a and b compare estimated slump values for PC-MK and FA-MK blends, respectively, with real data. This shows that the proposed models represented by Eqs (1) and (2) give a good prediction of the actual slump value from experimental results. The models are reliable and accurate and they can be used to predict the slump with a high degree of accuracy across a wide range of constituent materials.

Table 1. Correlation coefficients for predicting slump

Blends type	Model	Total replacement, %	α_0	α_1	α_2	α_3
PC-MK (FA = 0)	Eq. (1)	0–15	108.81	–9.429	0.190	0
FA-MK (FA ≠ 0)	Eq. (2)	10	37.5	–4.8	0.8	0
		20	34.286	–6.029	0.514	0
		30	–320.238	47.016	–2.133	0.03556
		40	582.500	–66.690	2.457	–0.02667

Table 2. Slump model summary

Model	Total replacement, %	R^2	Standard error of the estimate	F value	Residual (actual data-predicted data)	
					Maximum	Minimum
PC-MK (FA = 0) Eq. (1)	0–15%	0.998	1.5	1612	5	0.2
FA-MK (FA ≠ 0) Eq. (2)	10	0.995	2.2	94.5	1.5	0.5
	20	0.999	1.2	1984	1.3	0.4
	30	0.998	2.2	550	2.4	0.2
	40	0.999	1.7	1072	2.1	0.4

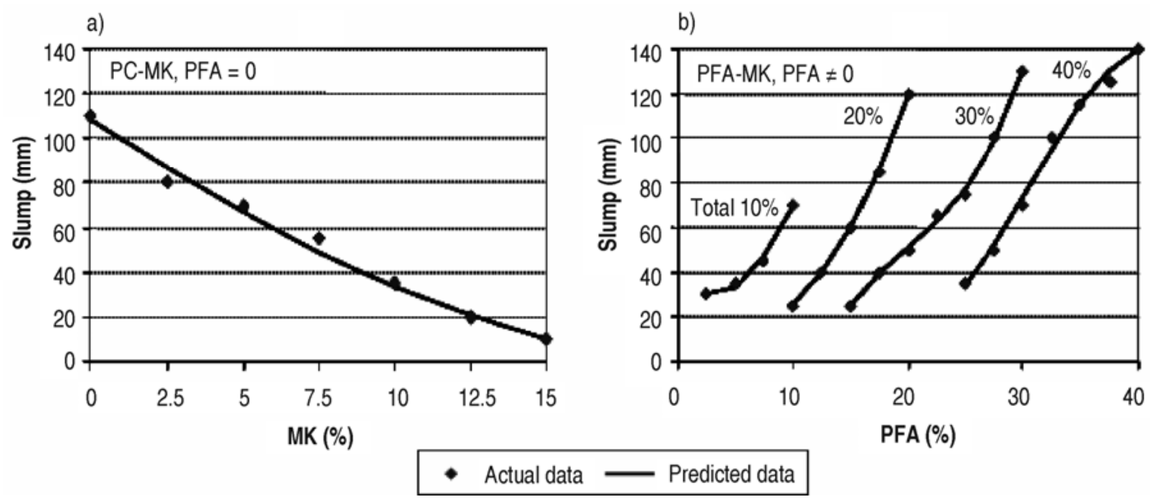

Fig. 1. Comparison and prediction of slump with statistical models

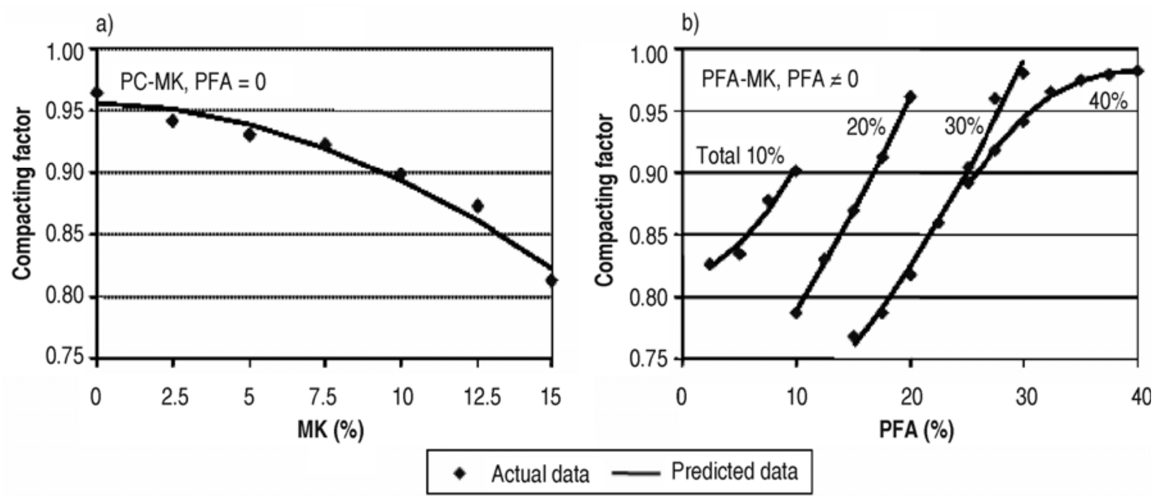

Fig. 2. Comparison and prediction of compacting factor with statistical models

3.3. Models for predicting compacting factor (CF)

A similar analysis to slump was carried out for compacting factor based on the standard compacting factor test results as shown in Fig. 2. The equations for predicting compacting factor of PC-MK and FA-MK blends, respectively, are shown below:

for PC-MK concrete (without FA)

$$CF = \beta_0 + \beta_1 M + \beta_2 M^2 , \quad (3)$$

for FA-MK concrete

$$CF = \beta_0 + \beta_1 P + \beta_2 P^2 , \quad (4)$$

where β_i are regression constants, $M = MK$ content (%), $P = FA$ content (%).

3.4. Models for predicting vebe time (VT)

The models for predicting vebe time (VT) were established on the basis of the data obtained. The equations used were as follows:

for PC-MK concrete (without FA)

$$VT = \gamma_0 + \gamma_1 M + \gamma_2 M^2 , \quad (5)$$

for FA-MK concrete

$$VT = \gamma_0 + \gamma_1 P + \gamma_2 P^2 , \quad (6)$$

where γ_i are regression constants; $M = MK$ content (%); $P = FA$ content (%).

Multivariate regression analysis and significance tests were carried out again. The best-fit coefficients of γ_i are obtained.

3.5. Guidelines for predicting consistency parameters

On the basis of the experimental data analysed, models have been established for predicting consistency parameters. The overall model is represented by the general equation:

$$\textit{workability parameter} \quad W = \sum_i \delta_i B^i , \quad \textbf{(7)}$$

where δ_i are constants, i from 0 to 3; B is blends content (%), either MK or FA.

W is the estimated consistency parameters which include slump, compacting factor and vebe time, corresponding to a given PC-FA-MK concrete mix. This can be used to predict consistency parameters corresponding to any given set of mix proportions. Since W is an estimated value, it will associate with it a degree of error which relates to the confidence prediction limits. If 95% of confidence intervals are obtained, this gives the prediction limit which is of practical significance and provides an indication of the reliability of consistency parameter prediction when using this method.

To obtain a simple and reliable model and a guideline for predicting consistency parameters practically, the following empirical rule (Wild *et al.* 1996) may be applied:

$$W_{pred} = W_{model} \pm 2\sigma , \quad (8)$$

where W_{pred} is suggested confidence prediction limits for consistency parameters; W_{model} – calculated value of consistency parameters from Eq (1)–(6), 2σ – statistical interval for W_{model} with 95% significance; σ – standard error.

This establishes that 95% of the values are within the range of the calculated value ± 2 standard errors.

From Table 2, all standard errors for estimating slump are less than 2.2, thus 2σ is less than 5 mm. For simplicity, 5 mm can be taken as the prediction interval, which increases the confidence of prediction and is in a very good agreement with the accuracy requirement specified by British Standards; similarly, 0.02 (2σ) and 1 second (2σ) based on statistical outputs can be reasonably and reliably taken as the prediction interval for predicting compacting factor and vebe time, respectively.

4. Conclusions

Development of a multivariate statistical model for consistency parameter prediction including slump, compacting factor and vebe time for concrete incorporating FA and MK is described. The models constructed provide an efficient, quantitative and rapid means for obtaining optimal solutions to consistency prediction for concrete mixes using PC-FA-MK blends as binder.

Based on the experimental data, comprehensive regression analysis and significance tests were performed and the best-fit models for predicting consistency parameters were found. Values of consistency were calculated by the proposed models and gave a good agreement with observed experimental data. It indicates that the models are reliable, accurate and can be used in practice to predict the consistency of PC-FA-MK blends.

On the basis of the models and the statistical analysis, Eq. 8 is suggested as a guideline for practical limitations in the prediction of consistency. The models developed for consistency and their confidence intervals are summarised in Table 3.

Acknowledgement

The authors are very grateful to EPSRC for funding the investigation. The authors would also like to thank ECC International Ltd and Ash Resources Ltd for the support provided.

Table 3. Summary of models and guidelines of consistency

Consistency parameter	Blends type	Model	Confidence interval (95%)
Slump	PC-MK, FA = 0	Eq. (1)	±5 mm
	FA-MK, FA ≠ 0	Eq. (2)	
Compacting factor	PC-MK, FA = 0	Eq. (3)	±0.02
	FA-MK, FA ≠ 0	Eq. (4)	
Vebe time	PC-MK, FA = 0	Eq. (5)	±1 sec
	FA-MK, FA ≠ 0	Eq. (6)	

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BETONO MIŠINIO IŠ LAKIŲJŲ PELNŲ IR METAKAOLINO KONSISTENCIJA

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Santrauka

Straipsnyje aprašyti cementbetonio mišinio su lakiaisiais pelenais ir metakaolinu konsistencijos (slankumo, sutankinamumo, Vebe rodiklio) tyrimai. Parenkant betono mišinių sudėtis buvo naudojami lakieji pelenai, kurie pakeisdavo iki 40 % portlandcemenčio ir metakaolinas, kurio buvo dedama iki 15 % cemento masės. Atitinkamai buvo keičiami ir portlandcemenčio kiekiai. Remiantis tyrimų rezultatais, pasiūlyti statistiniai modeliai įvairių sudėčių betono mišinio konsistencijai prognozuoti. Palyginus prognozuojamus ir eksperimentinių tyrimų betono mišinio konsistencijos rodiklius nustatyta, kad jie labai gerai koreliuoja. Todėl pasiūlytus statistinius prognozavimo modelius galima taikyti betonų technologijos praktikoje.

Reikšminiai žodžiai: betono mišinio konsistencija, regresijos modelis, prognozavimas, portlandcementis, lakieji pelenai, metakaolinas.

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