Strength and Durability of Concretes with Slag-Fly Ash-Portland Cement

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Synopsis: Composite cements containing portland cement (50%), fly ash (25%) and slag (25%), all interground at a Blaine fineness of about 400 or 500 m^2/kg, were produced.

Superplasticized concretes with a slump of 200-230 mm were manufactured by using sulfonated naphthalene (*SN*) or acrylic polymer (*AP*). The dosage of superplasticizers was a little higher (10% more) when finer cements were used.

The *AP* superplasticizer was more effective than that based on *SN* in terms of lower dosage (20% less) and lower water-cementitious material ratio (10% less) at equal workability. Consequently, higher compressive strength were obtained for concretes with the *AP* admixture rather than with the *NS* superplasticizer.

The better performance of the *AP* superplasticizer with respect to the *SN* admixture was independent of the curing temperature (5° or 20°) at early (1 day) and later ages (28-90 days).

All the concrete mixtures perform very well for the durability behavior in terms of lower CO_2 penetration and chloride diffusion. However, due to the lower water-cementitious material ratio (0.29 vs. 0.32) concretes with the acrylic polymer are potentially more durable than those with the naphthalene-based superplasticizer.

Keywords: Carbonation, Chloride Penetration, Composite Cement, Compressive Strength, Fly Ash, Slump, Slump Loss, Slag Superplasticizer.

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INTRODUCTION

Composite cements, based on ternary blends of portland cement, fly ash, and ground granulated blast-furnace slag, may be produced, in agreement with the European Standard EN 197/1(1), with a slag + fly ash content up to 60% (CEM V/A) or 80% by mass (CEM V/B). However, in Europe composite cements are not widely used in practice.

Previous works on ternary blends of portland cement, slag, and fly ash were studied by Berry (2), Swamy (3), Douglas and Pouskouleli (4), Nagataki (5), Dehuai and Zhaoyuan (6) and Collepardi et al. (7).

The main purpose of the present paper was to study the influence of different superplasticizers on concrete mixtures manufactured by using fly ash-slag-portland cement with a total portland cement replacement of 50% by mass. The following properties were examined: workability, slump-loss, compressive strength, and durability of concrete mixtures, all manufactured with a water-cementitious material ratio (*w/cm*) as low as about 0.3.

MATERIALS

Cementitious materials. The chemical analysis of the ingredients (portland cement, fly ash, and slag) used to manufacture blended cements are shown in Table 1.

Table 2 shows the composition of four composite cements (*A*, *B*, *C*, and *D*) all with 50% portland cement replaced by 25% of fly ash and 25% of ground granulated blast furnace slag, the main difference being the fineness of the three ingredients. Cements *A* and *C* were manufactured by blending unground fly ash with portland cement and slag ground at the same fineness (about 400 or 500 m^2/kg). Cements *B* and *D* were manufactured by blending ground fly ash with the other two ingredients at the same fineness (about 400 or 500 m^2/kg). In a previous paper (7) more details can be found for setting time and compressive strength of the four blended cements according to the EN 197/1 standard.

Aggregates. Natural sand (fineness modulus of 3.09) and two coarse aggregates were used. For all concrete mixtures a combined aggregate was used with 25% of sand, 40% of gravel (4-16 mm), and 35% of coarse aggregate (10-25 mm).

Superplasticizers. A 40% aqueous solution of sulfonated naphthalene-based (*SN*) superplasticizer or a 30% of acrylic polymer (*AP*) aqueous solution were used. Both superplasticizers came from Mapei, Milan (Italy).

Concrete mixtures. Table 3 shows the composition of concrete mixtures. The superplasticizer dosage (in the range of 0.8-1.1% by mass of cementitious material) was adjusted to obtain approximately the same slump level (200-230 mm) at about the same *w/cm* of 0.3.

The content of the cementitious material (including fly ash and slag) was about 470 kg/m^3 which corresponds to a content of portland cement of about 235 kg/m^3.

METHODS

The following properties were determined:

- slump just after mixing (5 min) and after some time of agitation at room temperature (slump loss);
- compressive strength of 100 mm-cube concrete specimens cured at 5°C or 20°C;
- depth of carbonation as measured by the phenolphthalein test (RILEM CPC – 18) of concrete specimens exposed to air after demoulding at 1 day;

- chloride penetration through the $AgNO_3$ and fluorescein test (8) of concrete specimens exposed to a 10% NaCl aqueous solution after a wet curing of 1 week and an air curing of 3 weeks.

RESULTS

Workability. Table 3 indicates that, at a given slump level, the *AP* admixture was more effective than the *SN*-based superplasticizers in terms of lower *w/cm* (10% less) of the concrete mixtures and lower superplasticizer dosage (20% less).

The increase in the specific surface area of the composite cement causes a negligible increase of the dosage of *SN*- or *AP*-based superplasticizer unless all the ingredients are ground at a Blaine fineness of about 500 m^2/kg as in the cement *D* for mixtures No. 4 and No. 8 of Table 3.

Slump-loss. Figure 1 shows the slump-loss curves of concrete mixtures with different superplasticizer type (*AP* vs. *SN*) or composite cements characterized by different fineness. For a given composite cement, the slump loss is much lower in concrete mixtures with the *AP*-based superplasticizer than in the corresponding mixture with the *SN*-based admixture.

On the other hand, for a given superplasticizer type (*SN* or *AP*), the slump-loss is mitigated by the use of cements with lower specific surface area (Fig.1).

Compressive strength. Figures 2, 3, 4 and 5 show the cube compressive strength results of concrete cured at 5°C and 20°C at R.H. of 95% for mixtures containing cements *A*, *B*, *C* and *D* respectively. In general, the compressive strength at 20°C is higher than that at 5°C at both early and later ages. However, even concrete specimens cured at lower temperature (5°C) reach strength levels as high as 35-50 MPa within 3 days. Although the portland cement content is as low as 235 kg/m^3, the strength level of all these concretes is relatively high at longer ages: 65-80 MPa at 28 days and 70-90 MPa at 90 days. This performance is related to the action of the cementitious activity of fly ash and slag combined with a *w/cm* as low as 0.3 due to the presence of superplasticizer.

The compressive strength of concrete with the *AP*-based superplasticizer is always higher (about 10% more) than that of the corresponding concrete with the *SN*-based admixture. However, the difference also depends on the specific surface area of the individual ingredients of the composite cement

Carbonation. Figure 6 shows the carbonation depth (x) as a function of time (t). After about 1 year of exposure to air, the carbonation depth is un-detectable or negligible in all the eight studied concretes. Then, that carbonation does not pose problems for corrosion of the metallic reinforcements due to very low permeability of these concretes containing high volumes of fly ash and ground slag.

Due, to the lower *w/cm* of concretes with the *AP*-based admixtures the carbonation rate is definitely lower with respect to that of the corresponding concretes with the *SN*-based superplasticizer.

The difference in the carbonation rate between concretes with cements characterized by different specific surface area is negligible.

Chloride penetration. Figure 7 shows the chloride penetration depth with time for the mixtures with composite cements.

Chloride penetration does not seem to depend on the fineness of the cementitious material of the composite cement.

Again, the chloride penetration rate is definitely lower in concretes with *AP*-based superplasticizer, with respect to those with the *SN*-based admixture, for the lower *w/cm* (0.29 vs. 0.32)

CONCLUSIONS

Superplasticized concretes with composite cements (25% fly ash, 25% ground slag, a 50% portland cement) perform very well in concrete mixtures in terms of good workability (190-220 mm), high compressive strength (65-80 MPa at 28 days), and excellent durability behavior (negligible carbonation and very low chloride penetration).

The compressive strength is slightly increased by the grinding action of both fly ash and slag.

The durability behavior does not seem to be significantly improved by increasing the fineness of the cementitious materials.

The superplasticizer based on acrylic polymer appears to be more effective than that based on sulfonated naphthalene in terms of lower *w/cm*, lower slump-loss, higher compressive strength and better durability behavior for the lower carbonation rate and chloride penetration.

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REFERENCES

1. European Standard EN 197-1, “Cement Composition, Specification and Conformity Criteria”, Part 1, Common Cements, 1992.

2. Berry, E.E., “Strength Development of Some Blended-Cement Mortars”, *Cement and Concrete Research*, V. 10, pp. 1-11, 1980.

3. Swamy, R.N., “Cement Replacement Materials”, Survey University Press, 1986.

4. Douglas, E., and Pouskouleli, G., “Prediction of Compressive Strength of Mortars Made with Portland Cement–Blast Furnace Slag-Fly Ash Blends”, *Cement and Concrete Research*, V. 21, pp. 523-534, 1991.

5. Nagataki, S., “Mineral Admixtures in Concrete: State of the Art and Trends”, ACI SP-144, pp. 473-484, 1994.

6. Dehuai, W., and Zhaouyan, C., “On Predicting Compressive Strength of Mortars with Ternary Blends of Cement, GGBFS and Fly Ash”, *Cement and Concrete Research*, V. 27, pp. 487-493, 1997.

7. Collepardi, S., Corinaldesi, G., Moriconi, G., Bonora, G., and Collepardi, M., "Durability of High Performance Concretes with Pozzolanic and Composite Cements", *Proceedings of CANMET-ACI Conference on Durability of Concrete*, Ed. V.M. Malhotra, Barcelona, Spain, 1999.

8. Collepardi, M., Marcialis, A., and Turriziani, R., “Penetration of Chloride Ions into Cement Pastes and Concretes”, *Journal of American Ceramic Society*, V. 53, pp. 534-535, 1972.

Table 1 – Chemical composition of portland cement, fly ash, and slag used to produce blended cements.

Oxyde (%)	**Portland cement**	**Fly Ash**	**Slag**
SiO_2	**21.25**	**59.94**	**36.50**
Al_2O_3	**4.33**	**22.87**	**11.67**
Fe_2O_3	**1.85**	**4.67**	**1.01[*]**
TiO_2	**0.13**	**0.94**	**0.20**
CaO	**64.30**	**3.08**	**38.95**
MgO	**1.81**	**1.55**	**8.08**
SO_3	**3.70**	**0.35**	**1.00[**]**
K_2O	**0.71**	**2.19**	**0.42**
Na_2O	**0.17**	**0.62**	**0.34**
l.o.i.	**1.50**	**3.34**	**1.28**

*as FeO **as S

Table 2 - Composition and Blaine fineness of composite cements CEM V/A

Blended Cement		**Portland Cement Fineness (m^2/kg)**		**Fly Ash**			**Ground Slag**	
				Unground	**Ground**	**Ground**		
				Fineness (m^2/kg)			**Fineness (m^2/kg)**	
Type	**Fineness (m^2/g)**	**395**	**504**	**351**	**395**	**482**	**412**	**517**
A	**384**	**50%**	**-**	**25%**	**-**	**-**	**25%**	**-**
B	**392**	**50%**	**-**	**-**	**25%**	**-**	**25%**	**-**
C	**472**	**-**	**50%**	**25%**	**-**	**-**	**-**	**25%**
D	**499**	**-**	**50%**	**-**	**-**	**25%**	**-**	**25%**

Table 3 – Composition of concrete mixtures.

Mix	**Total Cement Content**		**Gravel 10-25 mm**	**Gravel 4-16 mm**	**Sand 0-4 mm**	**Water**	**Super-plasticizer**	**w/cm**	**Slump**
No.	**Type**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(kg/m^3)**	**(type%cem)**		**(mm)**
1	**A**	**469**	**459**	**738**	**648**	**150**	**SN-1.00**	**0.32**	**220**
2	**B**	**471**	**461**	**741**	**651**	**150**	**SN-1.00**	**0.32**	**220**
3	**C**	**467**	**457**	**735**	**646**	**149**	**SN-1.05**	**0.32**	**200**
4	**D**	**472**	**462**	**744**	**653**	**151**	**SN-1.10**	**0.32**	**200**
5	**A**	**470**	**460**	**741**	**651**	**135**	**AP-0.80**	**0.29**	**230**
6	**B**	**473**	**463**	**745**	**655**	**135**	**AP-0.80**	**0.29**	**220**
7	**C**	**466**	**458**	**737**	**648**	**134**	**AP-0.80**	**0.29**	**210**
8	**D**	**474**	**464**	**746**	**656**	**136**	**AP-0.90**	**0.29**	**210**

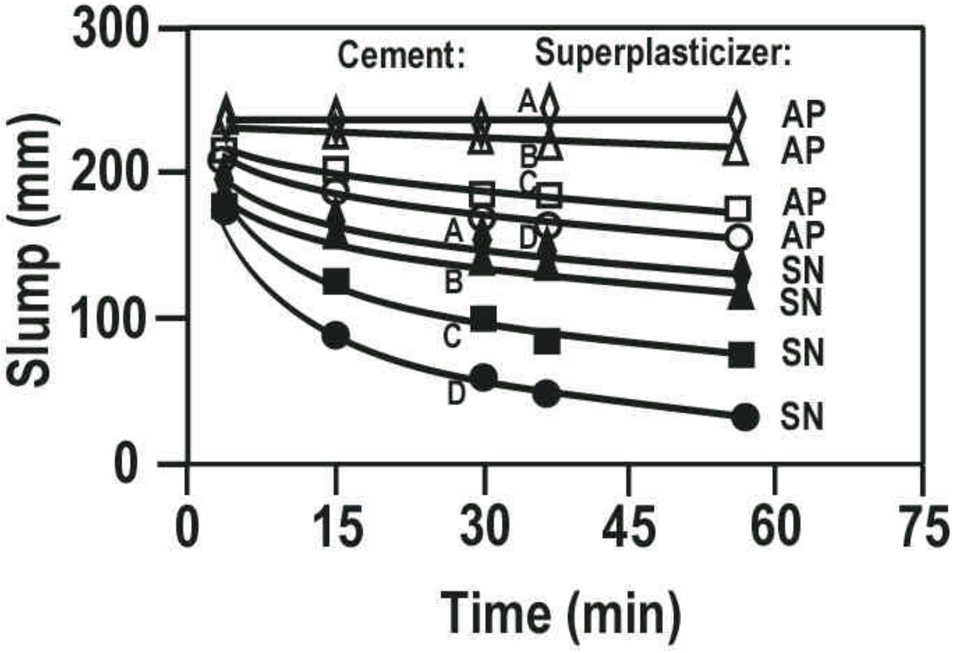

Fig. 1 - Slump-loss at 20°C of concrete mixtures with AP or SN superplasticizers (cements A, B, C and D in Table 2)

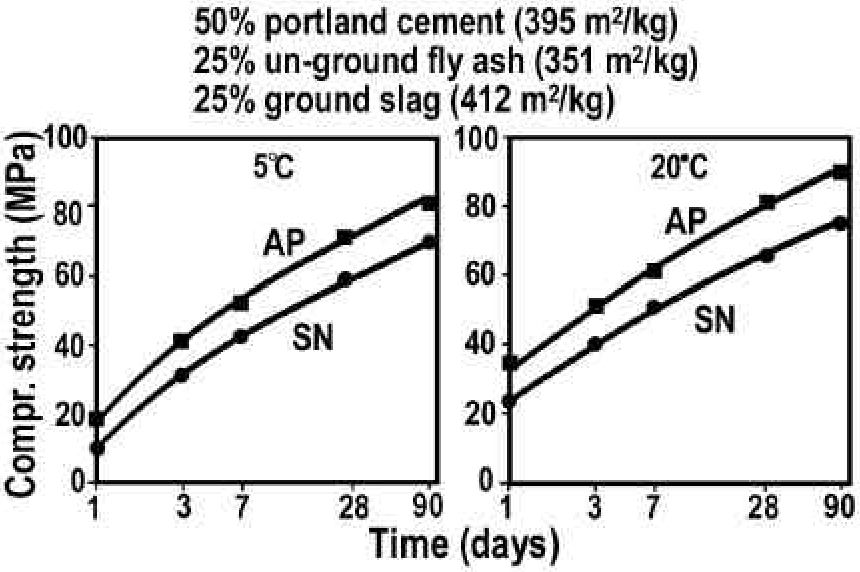

Fig. 2 - Influence of temperature and superplasticizer type on compressive strength versus time (cement A).

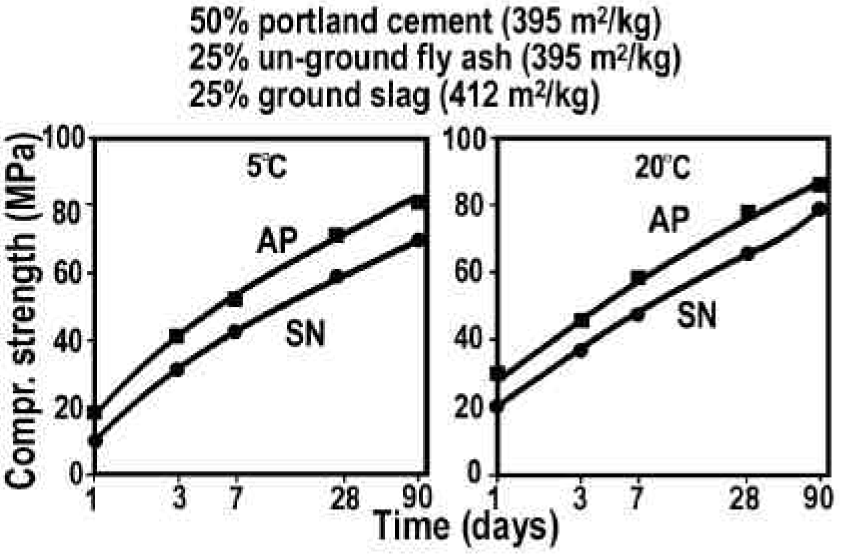

Fig. 3 - Influence of temperature and superplasticizer type on compressive strength versus time (cement B).

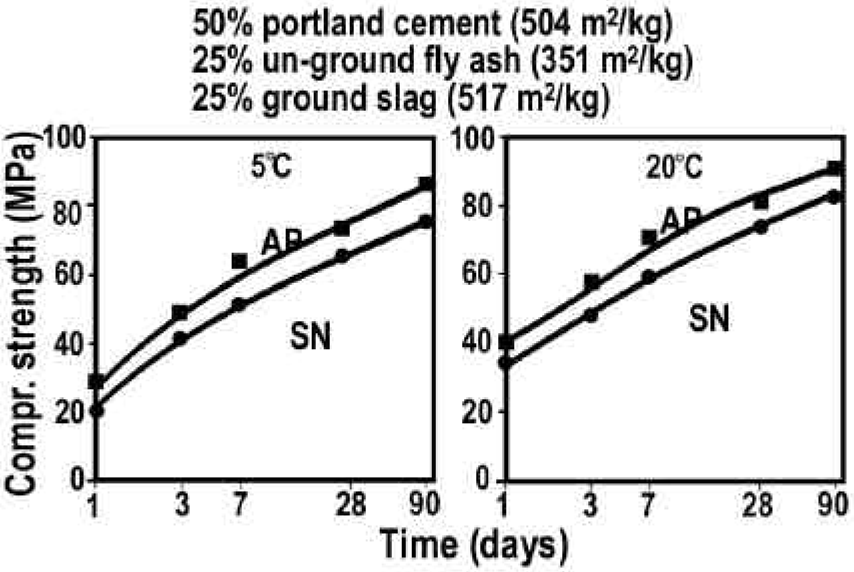

Fig. 4 - Influence of temperature and superplasticizer type on compressive strength versus time (cement C).

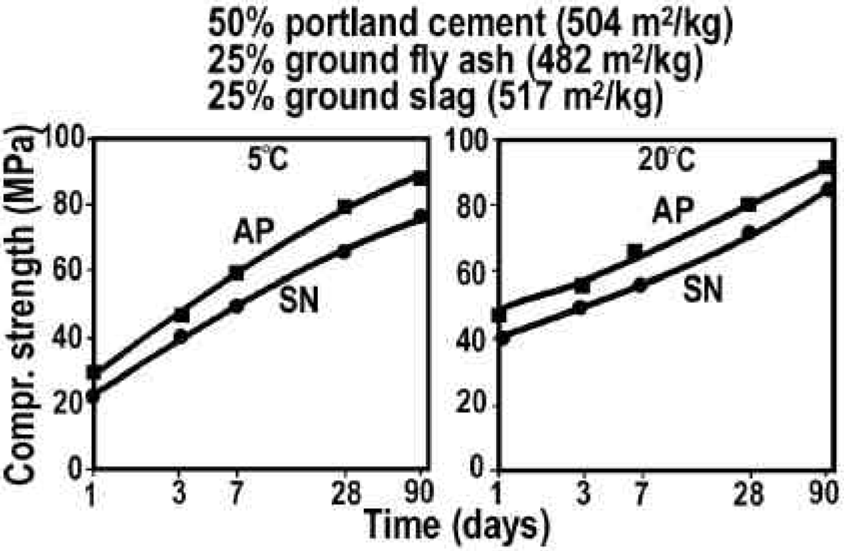

Fig. 5 - Influence of temperature and superplasticizer type on compressive strength versus time (cement D).

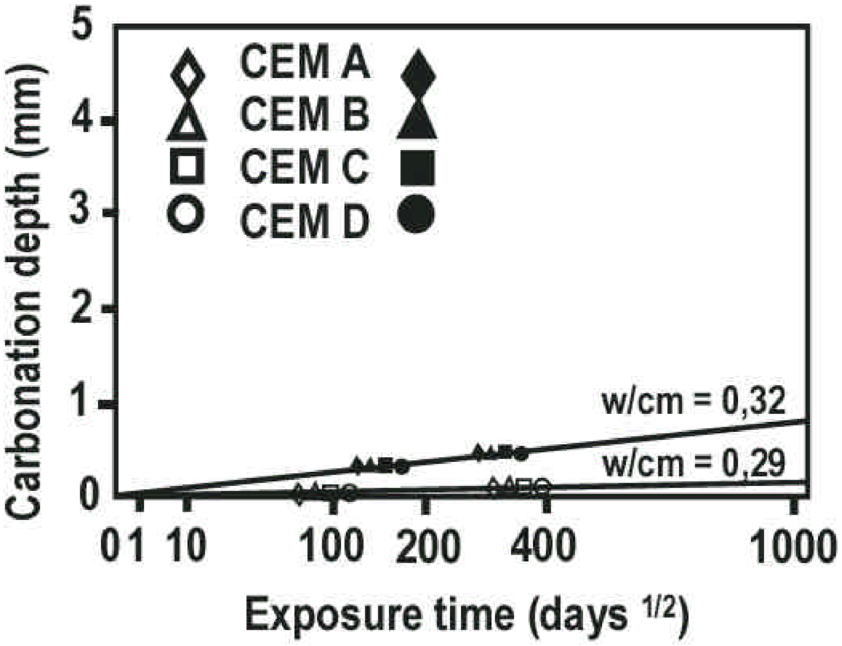

Fig. 6 - Carbonation depth in concrete mixtures with different w/cm.

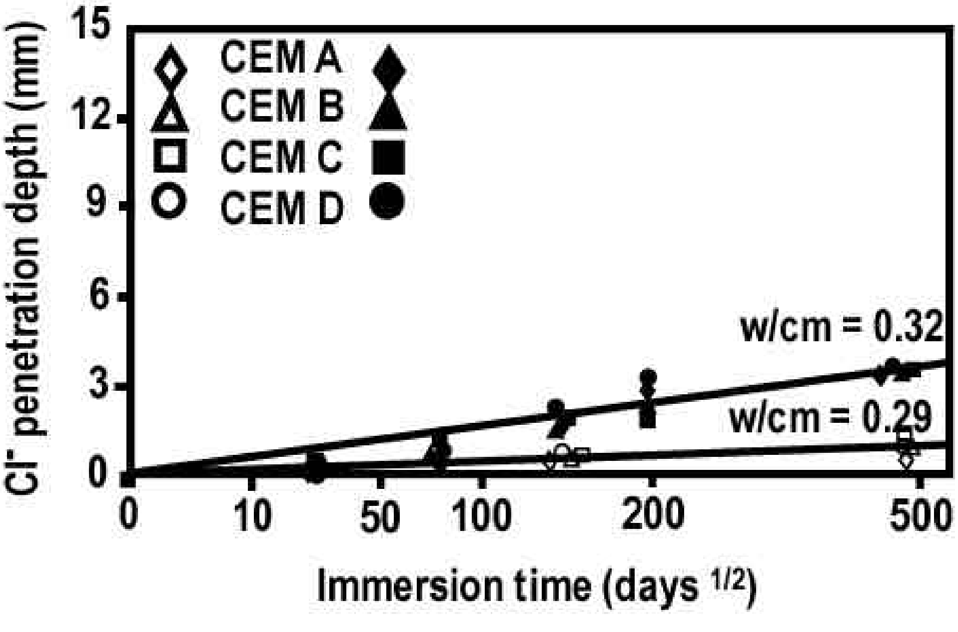

Fig. 7 - Chloride penetration in concrete mixtures with different w/cm