2nd International Symposium on Advances in Concrete through Science and Engineering
11-13 September 2006, Quebec City, Canada

MIX STABILITY AS A CRITERION FOR OPTIMIZING THE GRANULAR COMPOSITION TO IMPROVE CONCRETE DURABILITY - AN APPLICATION

X. Willem (1), L. Courard (2), A. Darimont (2) and R. Degeimbre (2)

(1) CRIB - Department of Civil Engineering, Laval University, Canada

(2) Department GeomaC, Research Unit on Building Materials, University of Liege, Belgium

Abstract

The aim of this study was to check the ability of an optimizing method of granular composition to improve concrete durability. The key of this approach was fresh concrete stability after casting.

In this work, the “natural consolidation” of concrete was the settlement of fresh concrete after casting, induced by the weight of the material and due to the expelling of water out of the inter-granular voids. This contraction can come into view with the graduated emergence of a layer of bleeding water on the top of the sample. The Phase Volume Distribution Model (PVDM) based on Powers' quantitative description of water binding in cement paste, was developed by the authors to estimate natural consolidation intensity from measurements of hardened concrete porosity. In previous work, the authors suggested that the more efficient hardened concrete for durability was the one with the lower porosity without being submitted to an intensive natural consolidation. To find the granular mixtures that need low water content for a given consistency and that give good mix stability, the authors used the Compressive Packing Model (CPM) developed by LCPC with a supplementary criterion. For given granular materials, they searched among the granular mixtures having a packing density close to the maximal value, for the one that had the richest amount of particles in the 0,125/0,500 mm range.

Using three different sources of sand, seven granular compositions were designed. The efficiency of granular mixtures was determined by the properties obtained on the basis of the same water-cement ratio and without admixture.

Good correlations were found between initial bleeding rate, bleeding capacity and calculated intensity of natural consolidation. It was showed that slump increases with the bleeding rate, except for the non-optimized mixture having the poorest fines content that exhibited a high bleeding rate with a low slump. Results confirmed that natural consolidation and slump depend on both packing density and fine particles content of the granular mix.

Desorption tests on hardened concrete showed that a higher degree of natural consolidation led to a lower volume of coarse capillaries. That means that an increased degree of natural consolidation, in the investigated range, improves hardened concrete structure. That was consistent with measurement of gas permeability and depth of carbonation: concrete having a higher degree of natural consolidation showed lower permeability.

This study highlighted the effect of concrete stability in the fresh state on the long-term performance of the material. Moreover, granular mix design made by using the Compressive Packing Model with a supplementary criterion based on fine particles content permitted to take into account concrete durability as a criterion of optimisation.

1. INTRODUCTION

Powers [1] was interested in the bleeding of fresh concrete because of data which indicated an important connection between the bleeding characteristics of the original mix and the durability of the concrete. The settlement of fresh concrete after casting, induced by the weight of the material, can come into view with the graduated emergence of a layer of bleeding water on the top of the sample [1]. The particles become more closely spaced than they were before bleeding began. The granular mix has undergone a consolidation, defined, according to geological, as the volume decrease induced by long term load due to the expelling of water out of the inter-granular voids, which leads to the transfer of the load from interstitial water to solid skeleton. The reactions of hydration can stabilize the granular skeleton

In this work, the phenomenon was called “natural consolidation” of concrete, to avoid confusion with consolidation processes used to expel entrapped air voids during the concrete casting.

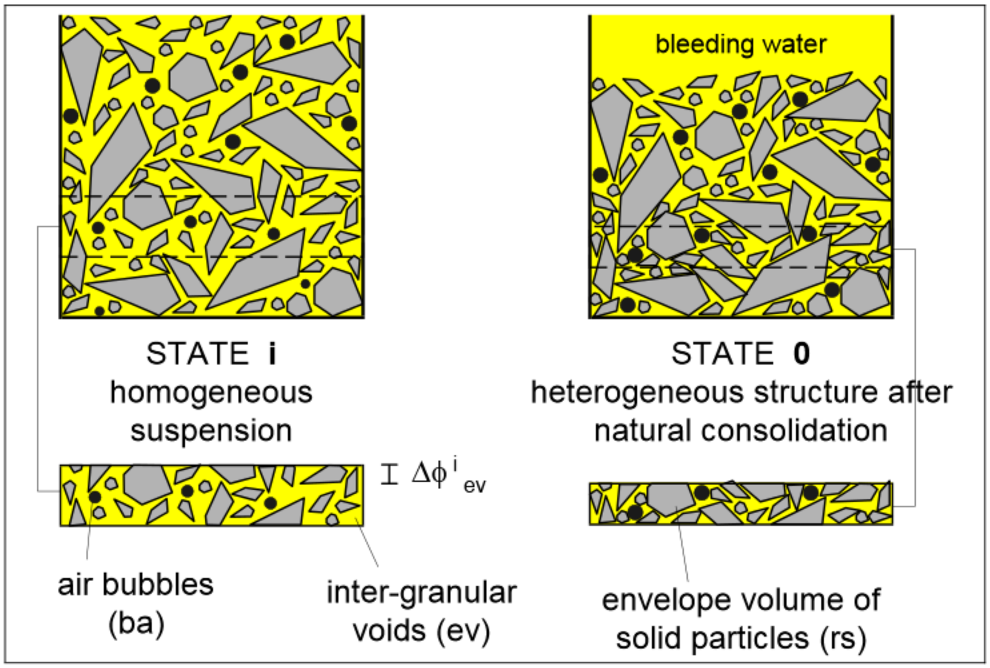

Figure 1: Natural consolidation of a cast concrete sample (degree of natural consolidation $\Delta\phi^i_{ev}$)

The natural consolidation phenomenon was seen (Figure 1) as the step between the "i" state defined as the mean granular structure of freshly cast sample, and the "0" state defined as the structure of particles reached when the setting occurs. The degree of natural consolidation $\Delta\phi^i_{ev}$ is the decreasing, relating to the "i" state, of partial volume of inter-granular spaces [m^3/m^3 of "i" structure].

In previous work [2], the authors developed the Phase Volume Distribution Model (PVDM) based on Powers' quantitative description of water binding in cement paste [3]. This model permitted to estimating of the degree of natural consolidation $\Delta\phi^i_{ev}$ from measurements of hardened concrete porosity.

Previous work [2] showed that the more efficient hardened concrete for durability was the one with the lower porosity without being submitted to an intensive natural consolidation. To find the granular mixtures that need low water content for a given consistency and that give good mix stability, authors used the Compressive Packing Model (CPM) developed by the LCPC [4] with a supplementary criterion. For given raw materials, they searched among the granular mixtures having a packing density close to the maximal value calculated with CPM, the one that had the richest amount of particles in the 0.125/0.500 mm range.

This paper presents an application of the optimizing method of granular composition in order to check its ability to improve concrete durability.

2. EXPERIMENTAL

2.1 Mix design

The raw materials were of local origin and a Portland cement CEM I 42.5R was used.

Table 1: Particle size distributions of aggregates

Sieve opening [mm]	Cumulative passing through the sieve [%]						
	FA 0/0.400	FA 0/2	FA 0/2.5	CA 2/7	CA 4/7	CA 7/14	CA 14/20
0.063	7.7	8.0	4.7				
0.125	11.6	11.0	6.3				
0.250	69.5	22.5	14.0	0	0		
0.500	100	39.5	26.3	0.5	1.5		
1.0		65.4	47.0	1.1	2.4		
2.0		93.5	78.2	7.6	4.3		
4.0		100	100	43.2	17.3		
7.1				95.1	83.5		
10.0				100	100	0	0
14.0						84.3	8.3
20.0						100	94
25.0							100

For designing mixtures, we chose among three fine aggregates: a siliceous fine rounded sand (0/0.400 mm) and two crushed hard limestone sands (0/2 and 0/2.5 mm). Coarse aggregates were provided among four gradings of crushed limestone (2/7, 4/7, 7/14 and 14/20 mm). The material grading curves are given in Table. 1. The other characteristics of aggregates needed for applying CPM were compiled in [2].

Based on previous research on fresh concrete behaviour [2], the chosen cement content, i.e. 325 kg/m^3, fitted with the optimal value for normal concrete without admixture. That means that this optimal cement content gave sufficient mix stability to reach the higher slump when water content was kept constant. The efficiency of granular mixtures was determined by the properties obtained on the basis of the same water-cement ratio and without admixture. Water content was maintained at a level, i.e. 180 l/m^3, sufficient for casting process by external vibrator and low enough to avoid excessive bleeding.

Seven granular compositions were designed (Table 2). Five compositions were optimized by using CPM and the last two, i.e. mixtures 1 and 5 came from an industrial plant. Differences between optimized mixtures were obtained by the selection of raw materials as optimizing variable and by fixing proportion. The calculated packing density $\phi_{rs\ CPM}$ was the partial volume of the particle envelopes (the real solid "rs") in the packing corresponding to consolidation of granular mix by vibration under load [1]. There were minor differences in calculated packing density $\phi_{rs\ CPM}$ between optimized mixtures. But the volume contents of the granular skeleton in the 0/0.125 mm range and 0.125/0.500 mm range (volume proportion) showed significative differences between mixtures.

Table 2: Composition of mixtures (proportions of raw materials that were chosen as optimizing variable are in bold)

Mixtures	1	2	3	4	5	6	7
Proportions (kg/m³)							
Water	180	180	180	180	180	180	180
Cement	333	333	333	333	333	333	333
FA 0/0,400	-	-	-	232	-	-	224
FA 0/2	-	-	-	-	695	**742**	**455**
FA 0/2,5	695	**891**	**896**	**592**	-	-	-
CA 2/7	213	**128**	**0**	**164**	213	**172**	**291**
CA 4/7	-	-	**98**	-	-	-	-
CA 7/14	675	**85**	**121**	**102**	675	**246**	**182**
CA 14/20	348	**826**	**816**	**835**	348	**770**	**774**
Characteristics of granular packing							
$\phi_{rs\ CPM}$	0.853	0.859	0.860	0.856	0.854	0.856	0.854
0/0.125 mm [%]	15.0	15.5	15.5	16.0	16.4	16.7	16.4
0.125/0.500 mm [%]	6.2	8.0	8.1	14.8	8.8	9.4	14.9

From the same raw material, optimizing led to an increase in packing density and in fine particles content, as it is shown by the shift of mix 1 to 2 and mix 5 to 6 in Figure 2. Adding a fixed proportion of sand FA 0/0.400 brought a lot of fine particles to the prejudice of packing density. The choice of raw materials seems having little effects, as illustrated for mix 3. The packing density increased lightly by replacing CA 2/7 with CA 4/7 without losing fine particle content.

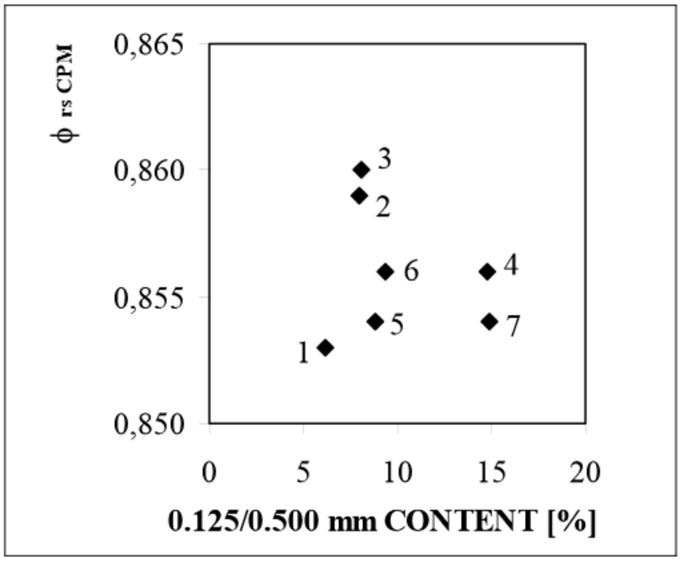

Figure 2: Main characteristics of granular mixtures – volume content of the granular skeleton in the 0.125/0.500 mm range and calculated packing density $\phi_{rs\ CPM}$

2.2 Tests

Bleeding test consisted in measuring the amount of bleed water according to NBN B14-205. Directly after mixing, concrete samples of 200 mm in height were cast in two cylindrical moulds of 160 mm in diameter. Every 30 minutes, the bleeding water was sucked after slightly tilting the mould and poured into a glass. Between each withdrawal, covers were placed upon the sample and the glass to lower the rate of evaporation. Amount of bleeding water per unit of surface was called height of bleeding. At the beginning of the test, the height of bleeding increases linearly in time [5]. We can define initial rate of bleeding R_{IB}. Bleeding capacity H_B is the maximum value reached by bleeding height.

The consistency was measured by a slump test (Sl) made 15 minutes after first contact between cement and water. Entrapped air content (A) was determined from the unit weight MV_{exp} of two concrete samples cast in cylindrical moulds (Ø160 × H320 mm) and consolidated on a vibrating table during 15 seconds.

A slab of $100\times600\times600$ mm^3 was cast and consolidated by external vibration. After demolding at one day, the slab was stored under water. Three prisms of 100×100 mm^2 of cross section area were sawn in the slab for carbonation test. The exposed sides perpendicular to the cross section were the upper trowel finished surface, the bottom cast surface and two surfaces sawn through the slab. From the middle thickness of slab were taken three cores (Ø150 × H50 mm) for permeability test and nine thin slices ($50\times10\times120$ mm^3) for desorption test. The tests started at 28 days after casting.

Test specimens for desorption were dried at 105°C until constant mass. Then, they were saturated under vacuum. Sets of three specimens for desorption were stored in different climate controlled boxes at 21 ± 2 °C until moisture equilibrium was reached. Relative humidity was maintained at 90, 93 and 97% with a saturated solution of $ZnSO_4$ 7 H_2O, KNO_3

and K_2SO_4, respectively. This procedure permitted to determine the apparent volume V_{app} of the test specimens (m^3), the actual porosity ε_{actual} (%), i.e. the volume proportion of total evaporable water measured on the saturated concrete slice, and the degree of saturation $\xi_{\%RH}$ of concrete in equilibrium with a fixed RH (%), using the following equations:

$$V_{app} = \frac{M_{sat\ spec} - M^{uw}{}_{sat\ spec}}{\rho_w} \tag{1}$$

$$\varepsilon_{actual} = 100 \times \frac{M_{sat\ spec} - M_{dry\ spec}}{\rho_w \cdot V_{app}} \tag{2}$$

$$\xi_{\%HR} = 100 \times \frac{M_{des\ spec} - M_{dry\ spec}}{M_{sat\ spec} - M_{dry\ spec}} \tag{3}$$

where $M_{sat\ spec}$ and $M^{uw}{}_{sat\ spec}$ were the masses (kg) of the saturated specimen measured in air and under water respectively, $M_{dry\ spec}$ the mass after drying at 105 °C, $M_{des\ spec}$ the mass of specimen in equilibrium with a relative humidity, and ρ_w the water density (kg/m^3).

According to Kelvin's law [6], the degree of saturation of concrete in equilibrium with 90, 93 and 97 % RH is the proportion of porous volume formed by pores finer than 10, 15 and 35 nm of radii, respectively.

The pre-conditioning of specimen and the measurement of gas permeability followed the recommendations of RILEM TC 116-PCD [7]. The test specimens were conditioned at intermediate average moisture concentration, which was in equilibrium with given relative humidity RH_{int}. By means of a CEMBUREAU permeameter with oxygen [8], the average gas flow rate Q (m^3/s) was evaluated at several pressures (1, 2, 3, 4 and 5 bar relative gas pressure). The apparent gas permeability k_{app} was calculated according to the Hagen-Poiseuille equation (4) as given below [9].

$$k_{app} = \frac{2\,Q\,P_{atm}\,L\,\eta}{A\,(P^2 - P_{atm}{}^2)} \tag{4}$$

where A and L were the cross-sectional area (m^2) and the thickness (m) of specimen respectively, η the viscosity of the gas ($N.s/m^2$), P the applied absolute pressure (N/m^2), and P_{atm} the atmospheric pressure (N/m^2).

The apparent gas permeability varies with the applied mean pressure [9]. According to the Klinkenberg concept [9], the "intrinsic coefficient of permeability k_{int}" defined by equation (5) is a characteristic of the porous network.

$$k_{app} = k_{int}\left[1 + \frac{\beta}{P_m}\right] \tag{5}$$

where β is a constant, characteristic of the porous solid and the percolating gas and P_m is mean pressure.

Carbonation test followed the prEN13295 [10]. Test specimens were exposed to 1% CO_2 air in a climate controlled container at 21 ± 2°C and 60 ± 10% RH.

3. RESULTS

Table 3 reviews the properties of fresh concrete. Good correlations were found between the initial bleeding rate and the bleeding capacity. Concretes held little entrapped air after consolidation by vibration. Adding of fine sand FA 0/0.400 led to the highest entrapped air content. In PVDM, the degree of hydration α took into account the time of hydration, the mineralogy of cement and the composition of cement paste, i.e. the water to cement ratio after natural consolidation [11,12].

Table 3: Properties of fresh concrete given by the mean value (standard deviation in brackets)

Mixtures	1	2	3	4	5	6	7
Fresh concrete							
Slump Sl (mm)	8	18	44	23	10	10	6
Bleeding Rate R_{IB} (10^{-3}.mm.min^{-1})	10 (1.0)	11 (1.9)	13 (1.2)	10 (1.0)	6 (0.2)	6 (0.5)	4 (0.3)
Bleeding Capacity H_B (mm)	1.1 (0.0)	1.2 (0.2)	1.2 (0.1)	1.2 (0.1)	0.8 (0.0)	0.6 (0.0)	0.5 (0.0)
Cast sample (based on results of two samples)							
Unit Weight MV_{exp} (kg/m^3)	2441 (1.0)	2420 (0.5)	2425 (8.5)	2397 (2.5)	2431 (1.0)	2433 (3.0)	2405 (4.0)
Air Content A (%)	0.2 (0.0)	1.1 (0.0)	0.9 (0.3)	1.8 (0.1)	0.6 (0.0)	0.5 (0.1)	1.5 (0.2)
PVDM (based on porosity of the nine specimens for desorption test)							
Degree of hydration α [kg/kg of cement]	0.63	0.64	0.63	0.65	0.64	0.64	0.65
Degree of natural consolidation $\Delta\phi^i_{ev}$ (m^3/m^3)	0.029 (0.005)	0.028 (0.004)	0.030 (0.008)	0.011 (0.008)	0.021 (0.005)	0.021 (0.005)	0.016 (0.007)

The dispersion of particles was sufficient for casting concrete by external vibrator as low air content showed (Table 3), but just enough to allow little motion of fresh mixture in slump test. Nevertheless the bleeding results showed a significant expelling of water. According to Powers [1], the packing density of granular mixture can be considered as the packing that natural consolidation tends to reach by expelling the excess water. So, the higher the packing density is, the higher the amount of excess water in the initial mix is, and the higher the bleeding capacity can be. Moreover, quantitative estimations were possible using CPM and PVDM models. The amount of excess water was in the 33 to 40 l/m^3 range. That was not much higher than the degree of natural consolidation (Table 3).

The supplementary criterion of mix design permitted to limit the bleeding rate of optimized mixtures by increasing the amount of fine particles that contribute a lot to water retention (Figure 3 and 4). Mixtures 1, 2 and 3 had at least the same bleeding rate as the other set of mixtures, i.e. 5 and 6. Increasing the content of fine particles by adding FA 0/0.400 did not decrease the bleeding rate significantly.

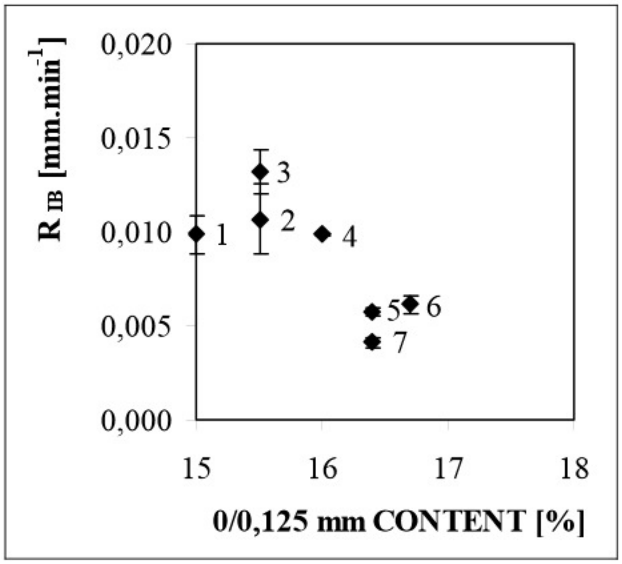

Figure 3: Bleeding rate R_{IB} of concrete vs. fines content of the granular skeleton

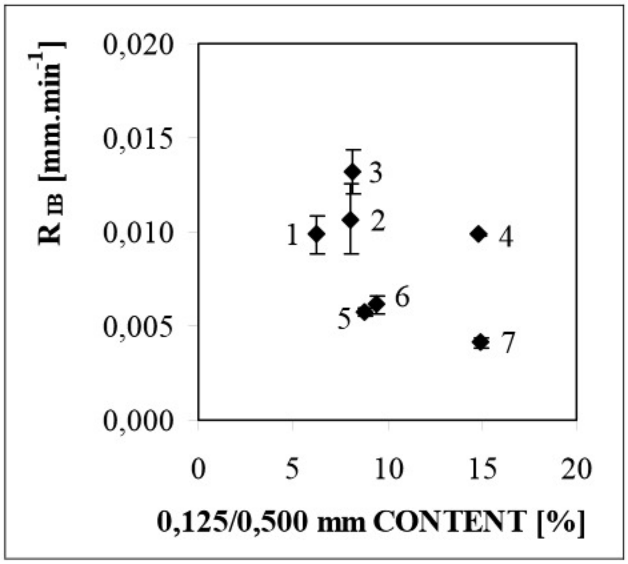

Figure 4: Bleeding rate R_{IB} of concrete vs. volume content of the granular skeleton in the 0.125/0.500 mm range

Increasing spacing between particles by improving packing density of granular composition affects the consistency. The supplementary criterion on the mix stability permitted the excess water to have its lubricating effect during the flow. The result was that slump increased with packing density (Figure 5). As confirmation (Figure 6), results showed a good correlation between slump and bleeding rate, excepted for the non-optimized mixture 1 having the poorest fines content that exhibited a high bleeding rate with a low slump.

The connection between bleeding and consistency highlighted Powers' belief that excessive bleeding and lack of workability could have the same source of causes [1].

By comparing Figures 5 and 6, it seems that mixture 4 contains as much excess water as mixture 2, thus should have the same packing density. The underestimate of the packing density of granular mix 4 can be due to the inefficient characterization of fine rounded particles of FA 0/0.400.

Using PVDM, we can calculate the porosity ε_{sd} of a concrete sample that would be obtained after a period of hydration if no natural consolidation occurred. The value of ε_{sd} after 28d of hydration was equal to 15 % for all the mixtures as they had the same water and cement content.

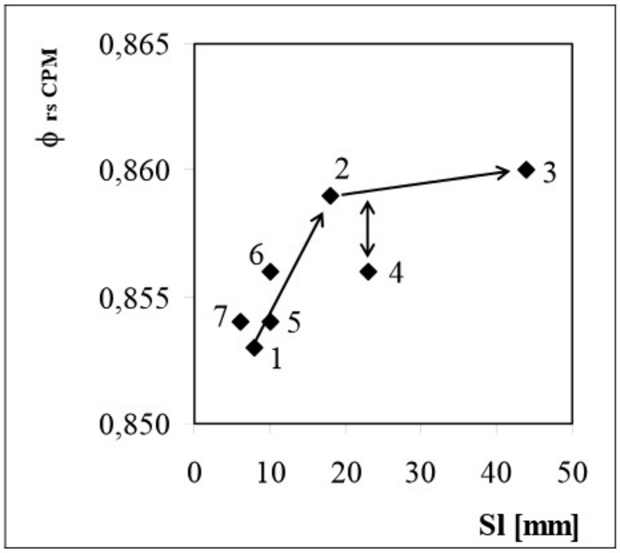

Figure 5: Calculated packing density $\phi_{rs\ CPM}$ of granular mixture vs. slump Sl

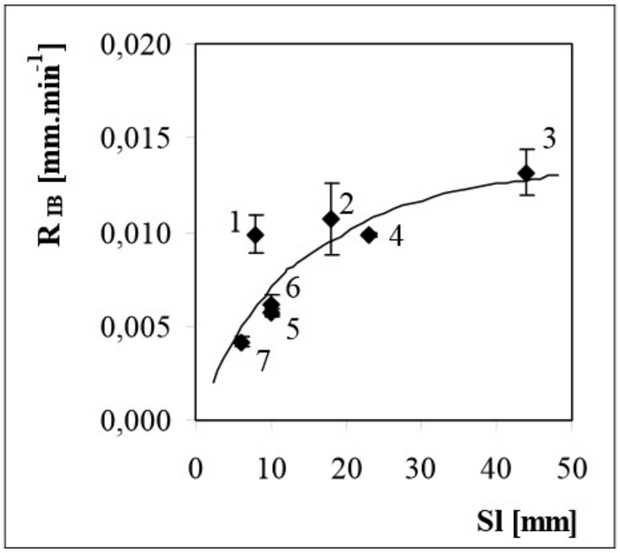

Figure 6: Bleeding rate R_{IB} of concrete vs. slump Sl

The fact that the calculated value ε_{sd} was higher than measured values ε_{actual} on hardened sample slices for each mix (Figure 7) means that concrete samples undergo natural consolidation, as bleeding measurements confirm (Figure 8). Moreover, a correlation appears between the bleeding rate and the calculated degree of natural consolidation.

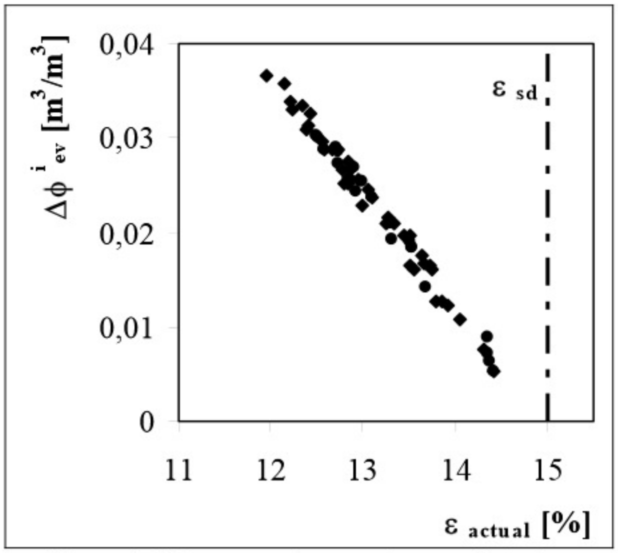

Figure 7: Degree of natural consolidation $\Delta\phi^{i}_{ev}$ calculated from the porosity ε_{actual} of all the specimens of desorption and all the mixtures

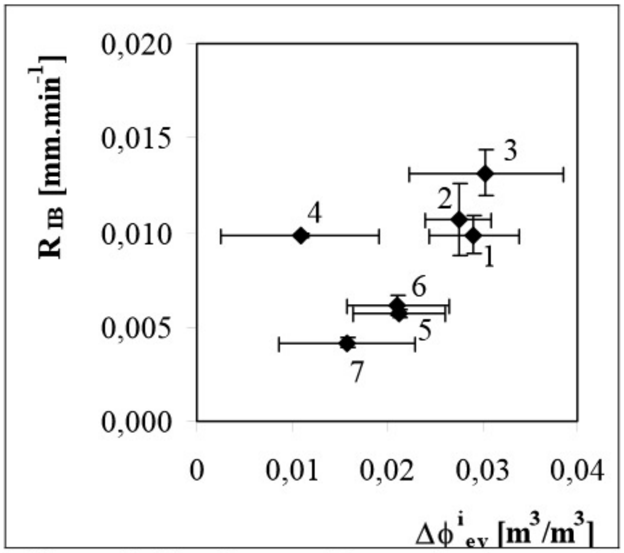

Figure 8: Bleeding rate R_{IB} vs. the degree of natural consolidation $\Delta\phi^{i}_{ev}$ calculated from porosity ε_{actual} of desorption specimens

Table 4: Properties of hardened concrete given by the mean value (standard deviation in brackets)

Mixtures	1	2	3	4	5	6	7
Mechanical properties (based on three samples)							
Compressive Strength R_c (MPa)	42.8 (1.4)	40.0 (1.9)	42.4 (1.0)	36.6 (1.1)	42.3 (0.5)	41.6 (0.5)	44.7 (2.2)
Tensile Strength R_t (MPa)	4.0 (0.1)	3.7 (0.6)	4.3 (0.8)	4.0 (0.2)	4.1 (0.3)	4.7 (0.3)	4.0 (0.1)
Desorption test (based on three test specimens)							
Porosity ε_{actual} (%)	12.7 (0.1)	12.7 (0.2)	12.5 (0.4)	14.0 (0.3)	13.3 (0.4)	13.3 (0.2)	13.6 (0.4)
Degree of saturation $\xi_{90\%RH}$ (%)	78.3 (2.7)	77.5 (1.2)	75.3 (2.4)	71.8 (2.8)	74.2 (0.4)	75.9 (1.5)	70.7 (1.0)
Degree of saturation $\xi_{93\%RH}$ (%)	84.9 (3.2)	84.7 (1.1)	81.6 (0.7)	81.3 (1.4)	80.9 (0.8)	78.7 (1.8)	74.6 (1.0)
Degree of saturation $\xi_{97\%RH}$ (%)	91.9 (2.3)	90.9 (1.7)	90.0 (2.5)	90.0 (2.1)	90.3 (0.7)	90.7 (0.6)	85.1 (1.9)
Gas permeability (based on three test specimens)							
RH_{int} after conditioning (%)	91 (2)	89 (2)	89 (1)	88 (1)	89 (1)	89 (2)	90 (1)
Intrinsic Permeability k_{int} (10^{-18}.m^2)	0.1 (0.0)	0.8 (0.1)	0.4 (0.1)	1.3 (0.2)	1.1 (0.3)	0.9 (0.2)	0.9 (0.2)
Constant β (10^5.Pa)	7.6 (0.7)	8.1 (1.3)	13.7 (1.5)	6.0 (0.2)	6.6 (3.0)	6.2 (2.4)	7.7 (1.2)
Depth of carbonation after 6 months of exposure (mm) based on three test specimens							
upper surface	2.3 (1.5)	1.3 (1.2)	5.0 (0.0)	5.3 (1.2)	3.0 (2.0)	2.7 (1.2)	4.0 (1.0)
lateral sawn surfaces	1.8 (1.7)	1.8 (1.2)	3.2 (1.0)	4.3 (1.4)	3.2 (1.2)	1.2 (1.0)	5.7 (3.5)
bottom cast surface	1.0 (1.0)	2.3 (0.6)	3.0 (3.0)	3.7 (1.5)	1.7 (0.6)	2.0 (1.0)	2.0 (0.0)

The indicators of durability, such as porosity, permeability and resistance against carbonation (Table 4) were compared to the behaviour of fresh concrete. Lower porosity of hardened concrete was connected with higher value of the degree of saturation of concrete in equilibrium with a fixed relative humidity (Figure 9). Thus, a higher degree of natural consolidation led to a lower volume of coarse capillaries. That means that an increase of the degree of natural consolidation, in the investigated range, improves hardened concrete structure (Figure 10). That was consistent with measurement of gas permeability (Figure 11) and depth of carbonation (Figure 12 and 13): concrete having a higher degree of natural consolidation showed lower permeability.

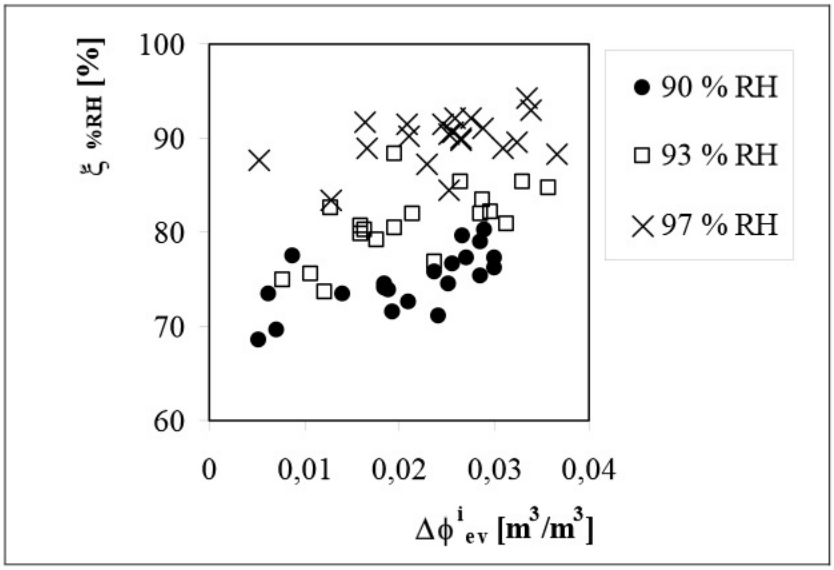

Figure 9: Degree of saturation $\xi_{\%RH}$ of concrete specimens in equilibrium with a fixed relative humidity vs. the degree of natural consolidation $\Delta\phi^{i}_{ev}$ calculated from their porosity

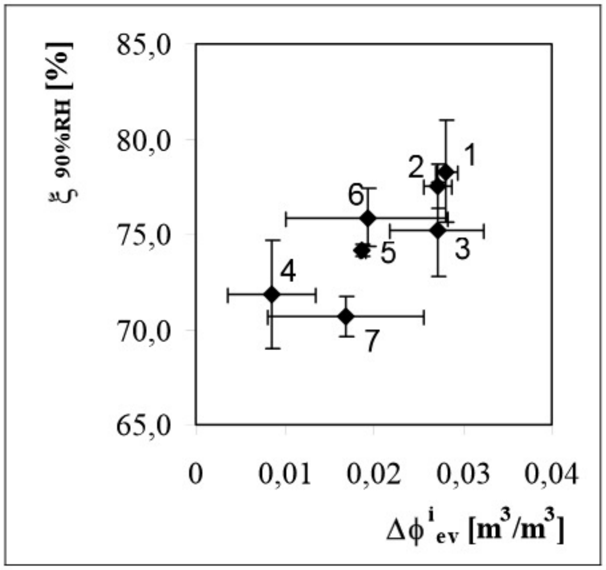

Figure 10: Degree of saturation $\xi_{90\%RH}$ of specimens in equilibrium with 90% RH vs. the degree of natural consolidation $\Delta\phi^{i}_{ev}$ calculated from their porosity

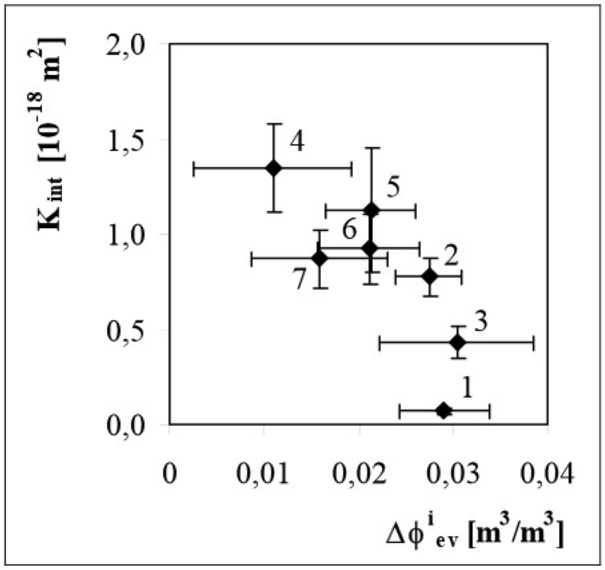

Figure 11: Gas permeability k_{int} vs. the degree of natural consolidation $\Delta\phi^{i}_{ev}$ calculated from the porosity of specimens of desorption

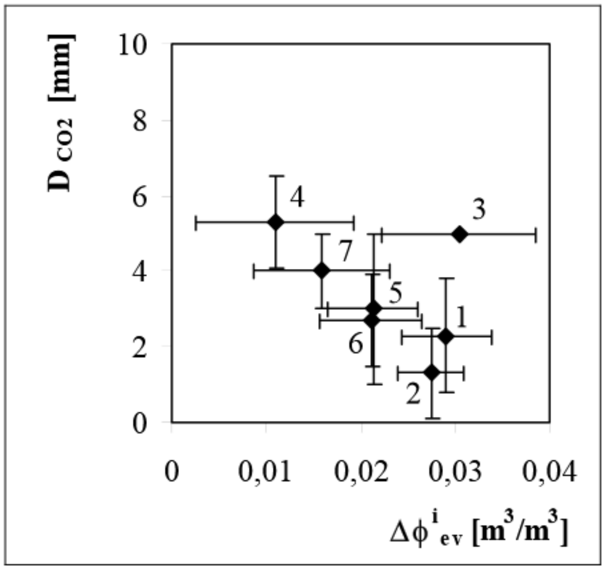

Figure 12: Depth of carbonation D_{CO2} measured on upper trowel finished side of slab after 6 months of exposure vs. the degree of natural consolidation $\Delta\phi^{i}_{ev}$

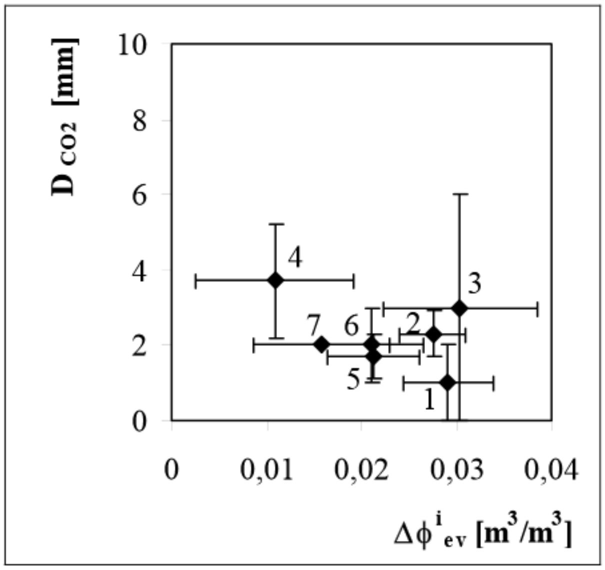

Figure 13: Depth of carbonation D_{CO2} measured on bottom cast side of slab after 6 months of exposure vs. the degree of natural consolidation $\Delta\phi^{i}_{ev}$

Natural consolidation seems to close the porosity and reduce the permeability of mass concrete. Nevertheless, the upper surface of mixture 3 that underwent highest bleeding rate was more permeable by CO_2 than concretes having just lower bleeding rate (Figure 12). Moreover, the bottom side of mixture 3 slab had many zones of weakness (Figure 13). In previous work [2], authors observed a limit value of natural consolidation above which the proportion of coarse capillaries increases. This justifies a careful inquiry into mix stability.

4. CONCLUSIONS

- Results showed a connection between natural consolidation and slump. Moreover, natural consolidation and slump depend on both packing density and fines content of the granular skeleton.
- Increasing the packing density of a granular mix necessitates control of its water retention ability
- Using the Compressive Packing Model with a supplementary criterion based on fine particles content permitted to optimize both consistency and stability of fresh concrete, depending on raw materials.
- Good correlations were found between initial bleeding rate, bleeding capacity and degree of natural consolidation calculated by PVDM from actual hardened concrete porosity.
- Tests on hardened mass concrete showed, in the investigated range of bleeding rate, that a higher degree of natural consolidation led to a lower volume of coarse capillaries and lower gas permeability. However, high bleeding intensity affected the permeability of concrete surface layer. So, the natural consolidation of conventional concrete should not

be encouraged even if it decreases the porosity. This study highlighted the effect of concrete stability in fresh state on the long-term performance of the material.

– Granular mix design by using the Compressive Packing Model with a supplementary criterion based on fine particles content permitted to take into account the concrete durability as a criterion of optimisation.

ACKNOWLEDGEMENTS

The research project was financially supported by the Regional Government of Wallonia, Belgium, under the Convention RW9813808. The authors express their sincere appreciation to the members of the Construction Materials Laboratory of the University of Liege, Belgium for their assistance in the realization of the tests.

REFERENCES

[1] Powers, T.C., 'The bleeding of Portland cement past, mortar and concrete treated as a special case of sedimentation', PCA Bulletin **2** (1939).
[2] Willem, X., 'Effects of natural consolidation on the indicators of concrete durability' (PhD Thesis of University of Liege, 2004) (only available in French).
[3] Brouwers, H.J.H., 'The work of Powers and Brownyard revisited: Part 1', Cement and Concrete Research **34** (2004) 1697-1716.
[4] de Larrard, F., 'Concrete mixture proportionning. A scientific approach', 1st Edn (E. & FN. SPON, 1999).
[5] L'Hermite, R., 'Expériences et théories sur la technologie du béton. Deuxième partie – Déformation du béton sans charge (retrait et gonflement)', Annales de l'ITBTP **375** (1979) 15-38.
[6] Haynes, J.M., 'Pore size analysis according to the Kelvin equation', Materials and Structures **33** (1973) 209-213.
[7] 'RILEM TC 116-PCD: Permeability of concrete as a criterion of its durability - Test for gas permeability of concrete', Materials and Structure **32** (1999) 174-179.
[8] Kollek, J.J., 'The determination of the permeability of concrete to oxygen by the Cembureau method – a recommendation', Materials and Structures **22** (1989) 225-230.
[9] Abbas, A., Carcassès, M., and Ollivier. J.-P., 'Gas permeability of concrete in relation to its degree of saturation', Materials and Structures **32** (1999) 3-8.
[10] European standard prEN 13295, 'Products and systems for the protection and repair of concrete structures – Test methods – Determination of resistance to carbonatation', (European Committee for Standardization, 2000).
[11] Schindler, A.K., Folliard, K.J., 'Influence of supplementary cementing materials on the heat of hydration of concrete', in 'Advances in Cement and Concrete IX Conference', Copper Mountain Conference Resort, Colorado, 2003.
[12] Powers, T.C., 'Physical properties of cement paste ', in 'Chemistry of Cement', Proceedings of the Fourth International Symposium, Washington, D.C., 1960 (National Bureau of Standards, U.S. Department of Commerce) 577-609.