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ORIGINAL ARTICLE

Minimum cement content requirements: a must or a myth?

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Abstract The objective of the present work was to systematically investigate the issue of minimum cement content requirements, by studying the behavior of concretes with different water to cement ratios (*w*/*c*) in the range of 0.45–0.70, in which the cement content was varied, by controlling the water content, using water reducing admixtures. The effect of cement content was noted to be different for various properties: strength was a function of *w*/*c* and independent of cement content; total water absorption was proportional to the paste content at a given *w*/*c*, while capillary absorption and chloride ingress reduced with a reduction in the cement content for a given *w*/*c*, to an extent which was much greater than the reduction in total porosity. Carbonation and shrinkage were largely independent of cement content for a given *w*/*c*. The trends observed were discussed in terms of the effect of paste content on concrete properties, and the influence of admixtures on the paste properties. These results suggest that requirements for minimum cement content in standards should be revisited.

Keywords Concrete · Cement content · Durability · Standard · Chloride penetration · Carbonation

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1 Introduction

Building codes worldwide set requirements for a minimum cement content in concrete, alongside limitations on maximum *w*/*c*. These requirements are not necessarily favorable from a technical and economical viewpoint; higher cement content is associated with greater cost and may lead to a higher sensitivity to cracking due to shrinkage and thermal effects. Further, due to environmental considerations there is a need to reduce the cement content in concrete, since this component has a relatively high environmental load due to the energy consumed and CO_2 emission involved in its production.

Little information is available in the literature which explicitly explains the reasoning for imposing minimum cement requirements in the standards. However, three arguments may be identified:

- Assurance of maximum *w*/*c*; this is a traditional approach which is probably the result of old practices when the only means to control *w*/*c* while maintaining workability without using admixtures was by changing the cement content
- The need for minimum content of fines (particles smaller than 0.075 mm) to assure workability and especially the development of proper bond between the concrete and reinforcing steel.
- For the protection of steel in concrete by chemically binding chlorides and CO_2 which penetrates into the concrete.

These arguments, especially the first two, are probably not relevant to modern concretes which are routinely produced with chemical admixtures that enable the production of sufficiently low *w/c* concretes while maintaining workability even with low cement contents. The need for fines content, if indeed relevant, can be met by using a range of fillers which are currently available in the industry [1]. The third argument, if indeed valid, might lead to the requirement of minimum cement content even in modern concretes.

Although the literature does not systematically address the issue of minimum cement content requirements [2], there are several studies which suggest that the cement content might be reduced without compromising durability performance [3–6]. In a recent study by the authors a similar indication was obtained, when studying the durability performance of dry concretes having low cement contents, and comparing their durability performance with fluid ones with higher cement contents [7].

The objective of the present work was to investigate systematically the issue of minimum cement content requirements, by studying the behavior of concretes with different *w/c* in the range of 0.45–0.70, in which the cement content is varied, by controlling the water content in the range of 160–200 kg/m^3 for each given *w/c*. This range of water content was achieved without compromising workability by adding water reducing admixtures. The effect of *w/c* and cement content on performance was studied by evaluating strength, total water absorption (representing the total open porosity), capillary absorption and penetration of chlorides and carbonation [8]. The influence of chemical admixtures was evaluated by studying the properties of pastes with identical composition to that of the paste in the concrete, i.e. similar *w/c* and admixture content.

2 Experimental

2.1 Concrete composition and preparation

The concretes evaluated were of four *w/c*: 0.45, 0.52, 0.60 and 0.70 at a slump in the range of 125–175 mm. Each concrete was prepared at three water contents (∼160, ∼180 and ∼200 kg/m^3 of concrete). The mixture with the highest water content of 200 kg/m^3 (and therefore the highest cement content) did not require any admixture (except for the 0.45 *w/c* ratio concrete), while the others were designed with water reducing admixtures, Rheobuild 700 (R700), Rheobuild 2000 (R2000) or Glenium 51 (G51), at a content which was adjusted to achieve the required slump. The aggregates were coarse aggregate (19 mm), medium aggregate (9.5 mm) and natural sand. The composition of the "base" concretes (200 kg/m^3 of water) is given in Table 1. The cement and admixture contents of all the mixtures are given in Table 2. These compositions represent a practical range for modern concretes, in which the cement content can be varied by about 25% for each *w/c* ratio by proper adjustments of the chemical admixture content and type.

The concretes were prepared in a pan mixer, in a five stage process: mixing of coarse and medium aggregates with 2/3 of the water content for 1 min and thereafter rest period of 10 min, adding cement, sand and the rest of the water and admixture and mixing for 3 more min. The concrete was cast and vibrated into the molds which were covered and

Table 1 Composition of "base" concretes with 200 kg/m^3 of water

Component, kg/m^3	*w/c* = 0.45	*w/c* = 0.52	*w/c* = 0.60	*w/c* = 0.70
Water	202	201	205	205
Cement	450	386	341	293
Coarse aggregate[a]	802	802	802	805
Medium aggregate[a]	401	401	401	403
Natural sand[a]	505	574	613	656
Admixture type	R700	–	–	–
Admixture content (% wt. of cement)	0.25%	–	–	–

[a] All aggregates are calculated in saturated surface dry condition

Table 2 Cement content and admixture type and contents of all the concretes investigated

Component	*w/c* = 0.45			*w/c* = 0.52			*w/c* = 0.60			*w/c* = 0.70		
Water content, kg/m^3	202	186	167	201	183	163	205	178	157	205	181	155[a]
Cement content, kg/m^3	450	413	372	386	351	313	341	296	262	293	259	221
Admixture type	R700	R2000	G51	–	R2000	G51	–	R700	G51	–	R700	G51
Admixture content, % wt. of cement	0.25	0.8	1.2	0	1.0	1.0	0	1.0	1.5	0	1.0	1.2
Paste content, % vol. of concrete	34.7	31.9	28.7	32.5	29.6	26.4	31.5	27.3	24.1	30.0	26.5	22.6

[a] Poor workability due to lack of fines

demolded after 1 day. The concrete specimens were kept for 6 more days in a fog room at 20°C and thereafter in the laboratory air, until testing.

2.2 Concrete testing

Strength—100 mm cubes were prepared and tested at ages up to 90 days. In the present paper only the 28 days results will be presented.

Free drying shrinkage—Shrinkage was determined by testing the length change of 70 × 70 × 280 mm specimens in drying conditions at 50%RH/20°C. The specimens were exposed to these conditions after 7 days of moist curing and if any autogenous shrinkage had developed it would mostly have been within this period.

Total absorption—Oven-dry disc specimens were immersed in boiling water at 28 days for 3 h, cooled down slowly to room temperature, and then dried in an oven to a constant weight. Total absorption was calculated as the weight loss on drying from saturated surface dry conditions to oven dry condition.

Capillary Absorption—The capillary absorption was determined according to EN 772–11, [9], using cylindrical specimens (200 mm diameter and 50 mm height). The specimens were dried at 55 ± 2°C, sealed with bitumen at the top and the cylindrical sides, and then immersed in water to a depth of 5 mm. The weight increase over time was measured, and the capillary absorption coefficient was calculated from the slope of the curve of weight increase vs. square root of time.

Chloride penetration—Chloride penetration was determined by the ASTM C1202 test, for specimens cured for 90 days.

Accelerated carbonation—Accelerated carbonation was determined by exposure of 90 days old samples to environment of 5% CO_2/50%RH/30°C and testing the depth of carbonation at predetermined time periods. Carbonation coefficient was calculated from the slope of the curve of carbonation depth vs. square root of time.

2.3 Cement paste tests

Pastes of *w/c* = 0.45 and 0.70 were prepared with identical admixture content as in the relevant concretes at these *w/c* ratios. The intention was to study the influence of the admixture on the paste component of these concretes. Cylinders, 47 mm in diameter and 280 mm in length were prepared. To assure uniformity and prevent segregation the samples were mounted on a rotating wheel immediately upon casting and were rotated until setting has occurred.

The specimens were tested for free shrinkage under conditions similar to the concrete specimens, to determine shrinkage strain and weight loss.

3 Results

3.1 Effect of cement content on mechanical and physical properties

The effect of cement content at the various *w/c* ratios on strength, total absorption and capillary absorption coefficient are presented in Figs. 1–3. It can be seen that strength is independent of cement content for a given *w/c* ratio, while total absorption and capillary absorption coefficient decrease with decrease in cement content. These trends are consistent with the current prevailing concepts that strength is a function mainly of *w/c* ratio, while total absorption and capillary absorption coefficient are dependent on the paste content of the concrete. Strength increases with

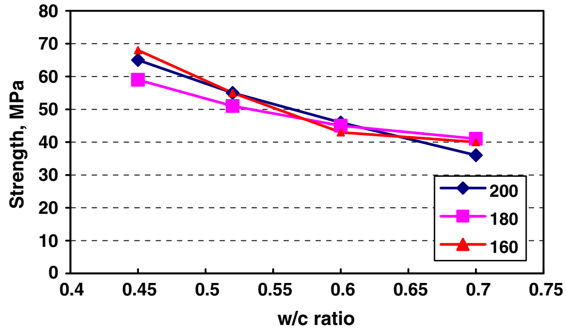


Fig. 1 Effect of cement content (i.e. different levels of water contents of about 160, 180 and 200 kg/m^3 of concrete) on 28 days compressive strength

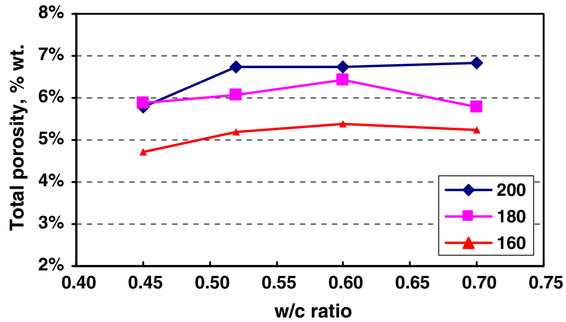


Fig. 2 Effect of cement content (i.e. different levels of water contents of about 160, 180 and 200 kg/m^3 of concrete) on total absorption

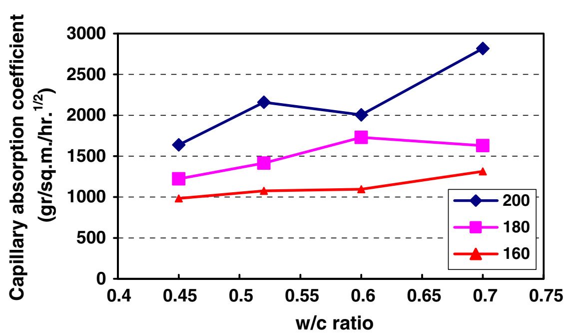


Fig. 3 Effect of cement content (i.e. different levels of water contents of about 160, 180 and 200 kg/m^3 of concrete) on capillary absorption coefficient

reduction in *w*/*c*, while total absorption and capillary absorption coefficient decrease with a reduction in *w*/*c*. The decrease in capillary absorption coefficient seems to be greater than that of total absorption, mainly with low *w*/*c* mixtures. This may be readily accounted for by the reduction in paste content at lower *w*/*c*, which affects both, total and capillary absorption, and additional influence of the refinement of the pore structure at lower *w*/*c* which would affect mainly the capillary absorption.

3.2 Effect of cement content on penetration of chlorides and carbonation

The effect of cement content at different *w*/*c* on the penetration of chlorides and carbonation is presented in Figs. 4 and 5, respectively. Both properties are much more sensitive to the effect of *w*/*c* ratio than total absorption and capillary absorption (Figs. 2 and 3); the effect of decreasing *w*/*c* on the reduction of chloride penetration and carbonation is much greater than its effect on total absorption and capillary

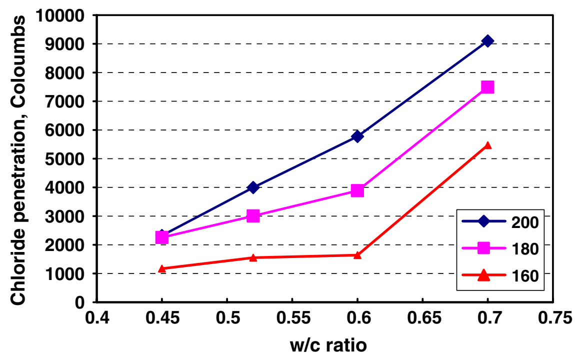


Fig. 4 Effect of cement content (i.e. different levels of water contents of about 160, 180 and 200 kg/m^3 of concrete) on chloride penetration

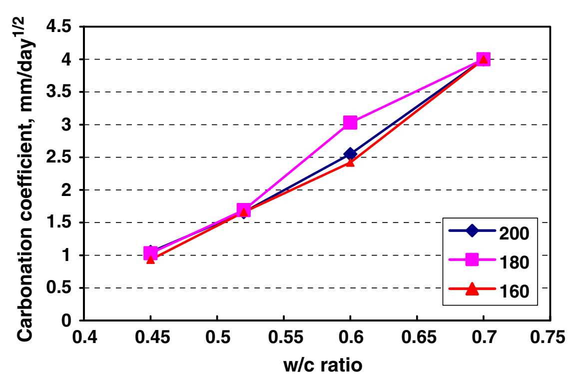


Fig. 5 Effect of cement content (i.e. different levels of water contents of about 160, 180 and 200 kg/m^3 of concrete) on carbonation coefficient in accelerating conditions

absorption. Yet, there is a considerable difference between the effect of the cement content at a given *w/c* ratio on chloride penetration and carbonation: reduction in cement content at a given *w/c* ratio leads to a marked reduction in chloride penetration (Fig. 4), while carbonation is practically independent of cement content (Fig. 5).

3.3 Effect of cement content on shrinkage in concretes

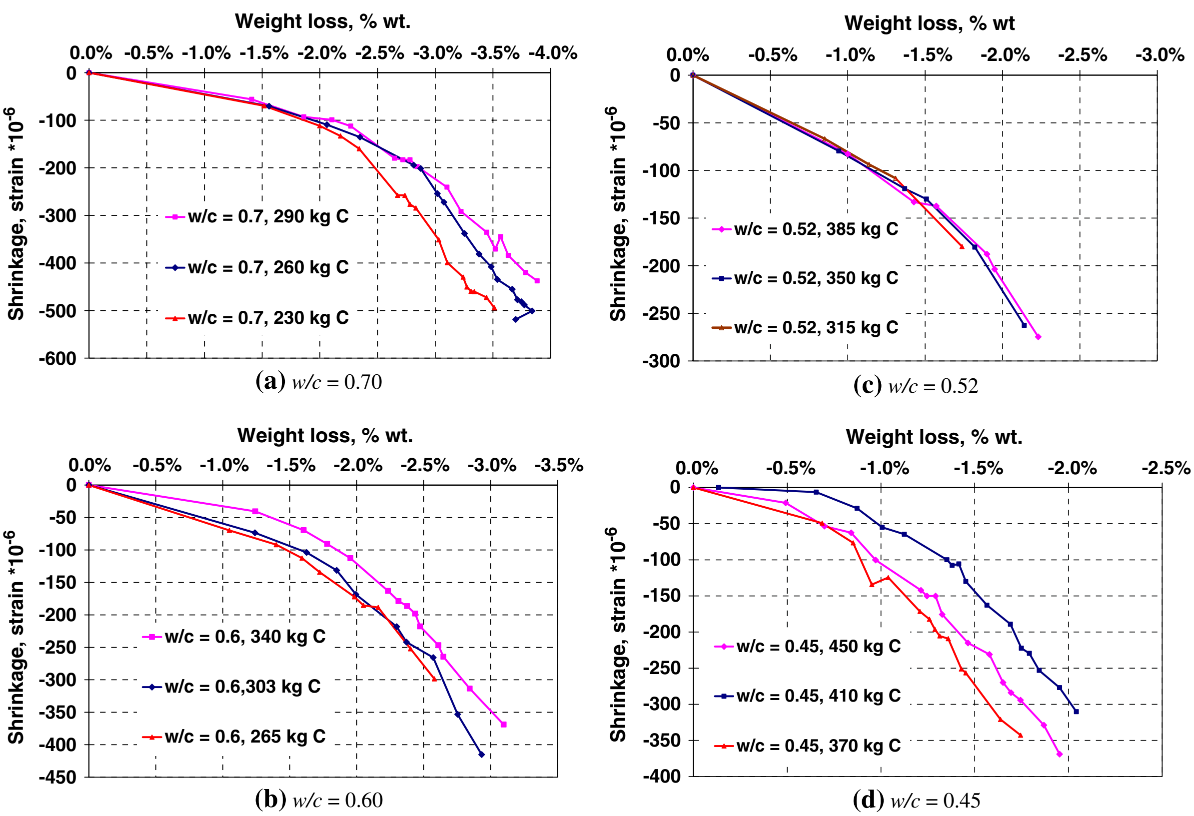
Typical curves showing the effect of cement content on shrinkage vs. weight loss at a given *w/c* are shown in Fig. 6. The shrinkage curves for mixtures of different *w/c* concretes having water content of about 200 kg/m^3 is shown in Fig. 7 (these are the mixtures with the highest cement content for each set of *w/c* ratio concretes).

For a given *w/c* the shrinkage does not seem to be affected much by the cement content (Fig. 6), and the slight differences in the shrinkage curves for a given *w/c* ratio cannot be related to a trend in a change in the cement content. For example, in Fig. 6d the highest shrinkage does not occur with the highest cement content. These findings coincide with the findings of [1] where increased paste content was used to control the workability instead of using admixtures.

The overall effect of *w/c* on the shrinkage, for concretes having the same water content of 200 kg/m^3 (Fig. 7) suggests that the effect of *w/c* ratio on shrinkage strains is rather small: the 0.70, 0.60 and 0.52 *w/c* ratio concretes have similar shrinkage curves while that of the 0.45 *w/c* ratio concrete is slightly lower (it should be noted, though, that the latter mixture contained an admixture whereas the others did not).

3.4 Effect of admixtures on shrinkage of pastes

The effect of the admixture content and type on the shrinkage of pastes of the same *w/c* ratio is presented



(a) *w/c* = 0.70 **(c)** *w/c* = 0.52 **(b)** *w/c* = 0.60 **(d)** *w/c* = 0.45

Fig. 6 Effect of cement content on shrinkage—weight loss curves of concretes having the same *w/c* ratio but differing in their cement content. (**a**) *w/c* = 0.70, (**b**) *w/c* = 0.60, (**c**) *w/c* = 0.52, (**d**) *w/c* = 0.45

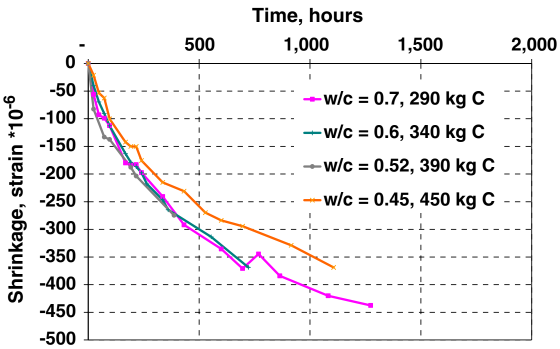


Fig. 7 Effect of *w/c* on shrinkage-time curves of concretes having a similar water content of about 200 kg/m^3

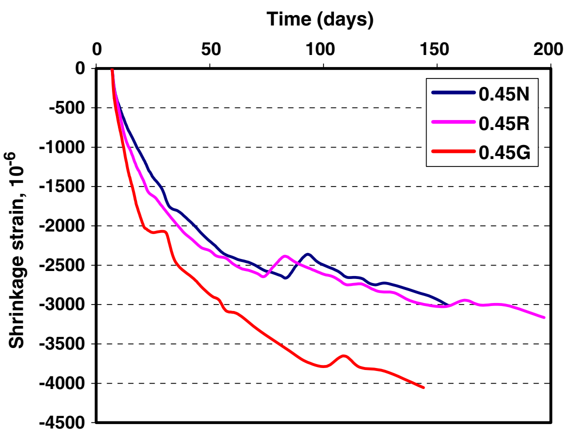


Fig. 8 The effect of admixture content and type on the shrinkage of $w/c = 0.45$ paste (0.45 N—without admixture; 0.45R—with Rheobuild 2000 admixture; 0.45G—with Glenium admixture)

in Figs. 8 and 9 for 0.45 and 0.70 *w/c* pastes, respectively. It can be seen that the admixture had an influence on shrinkage, with the Glenium admixture increasing the shrinkage in the 0.45 paste and the Rheobuild admixture increasing the shrinkage in the 0.70 paste. The series of paste studies was a preliminary one and did not cover systematically all the paste variables. It was intended to explore whether the chemical admixtures affect the paste properties for a given *w/c*. The results presented here indicate that indeed the admixtures have an effect on paste properties which show up, at least for some of them, by an increase in shrinkage. In addition, the final shrinkage of $w/c = 0.45$ paste was smaller by about 25% than that of the $w/c = 0.70$ paste.

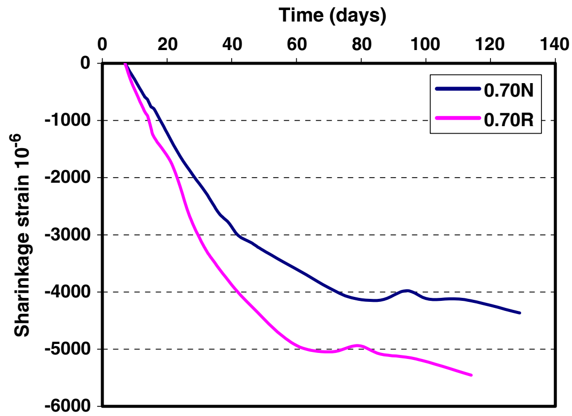


Fig. 9 The effect of admixture content and type on the shrinkage of $w/c = 0.70$ paste (0.70 N—without admixture; 0.70R—with Rheobuild 700 admixture)

4 Discussion

4.1 Strength and penetration

The relative effect of the cement content at the different *w/c* ratio concretes is plotted in Figs. 10 and 11 for the mixtures with 160 and 180 kg/m^3 water content (relative to the mixtures with 200 kg/m^3 water), respectively. The properties in each of these figures are strength, total absorption, capillary absorption coefficient, chloride penetration and carbonation. In Fig. 10, the reduction in cement content at each *w/c* ratio is about 20%, while in Fig. 11 it is about 10%.

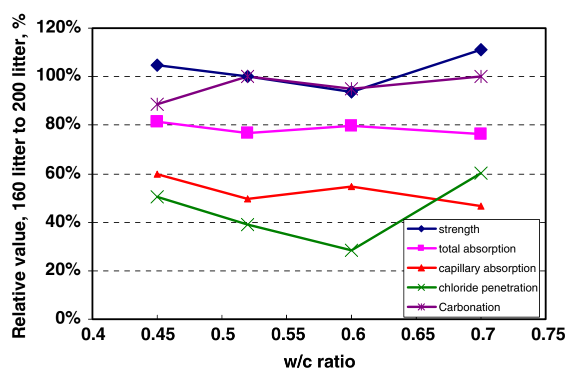


Fig. 10 The effect of cement content on the relative values of strength, total absorption, capillary absorption, chloride penetration and carbonation for mixtures with about 160 kg/m^3 water content relative to mixtures with about 200 kg/m^3 of water, i.e. cement content reduction of about 20%

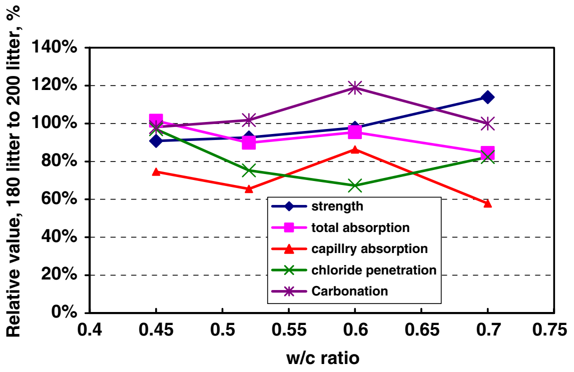


Fig. 11 The effect of cement content on the relative values of strength, total absorption, capillary absorption, chloride penetration and carbonation for mixtures with about 180 kg/m^3 water content relative to mixtures with about 200 kg/m^3 of water, i.e. cement content reduction of about 10%

These figures clearly demonstrate that for each property the effect of cement content can be quite different. The trends for the differences are more obvious in Fig. 10 since it represents mixtures where the differences in cement content are about 20%. It can be seen from Fig. 10 that strength and carbonation are practically independent of cement content, while capillary absorption and chloride penetration are reduced significantly, ~50%. The latter reduction is significantly greater than the reduction in total absorption, which is roughly 20%. The trends outlined are more or less the same for the range of *w*/*c* ratios studied here, 0.45–0.70.

These trends suggest that the effect of cement content cannot be generalized, and for different properties its influence is different. Some of the trends can be readily explained on the basis of prevailing concepts in concrete technology:

- Strength is a function of the *w*/*c* of the paste in the concrete. If the change in cement content is achieved without compromising the workability (by the use of admixtures, for example), the concrete strength should be independent of cement content, as shown in Figs. 10 and 11.
- Total absorption is a measure of the total porosity of the concrete. For concretes of similar *w*/*c* and degree of hydration, the total porosity should be linearly proportional to the paste content. Indeed, the reduction in total absorption is about 20 and 10% in Figs. 10 and 11, which corresponds to the reduction in the paste content in these concretes (Fig. 12).

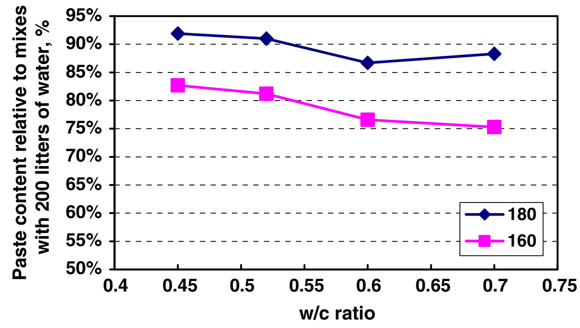


Fig. 12 The paste contents in concretes with about 160 and 180 kg/m^3 of water relative to the 200 kg/m^3 water content concretes

One would have expected that the capillary absorption coefficient would also be proportional to the paste content, as the total absorption. However, the relative reduction in capillary absorption coefficient is much greater than the reduction in the paste content, which suggests that an additional factor is having an influence here. Such a factor may be the pore size distribution, which would not affect total porosity but would influence the capillary absorption rate. An indication that this may be a viable explanation is supported by the shrinkage data of the paste tests, which suggest that the presence of the water reducing admixture (presence which is essential in the lower cement content concretes) is apparently causing changes in the paste structure, perhaps refining it and also changing the surface tension. This implies that when assessing the influence of the cement content on capillary absorption, there is a need for evaluating the influence of the water reducing admixture on modification of the pore structure, and not just its influence on the reduction in water content.

The reduction in chloride penetration with reduction in cement content is similar to that of the capillary absorption, i.e. a reduction which is considerably greater than that of the total porosity. The explanation for this effect can be based on similar concepts as those outlined for the capillary absorption, namely effects of the water reducing admixture on the pore size distribution.

When assessing the overall effect of chloride, one should consider not only the effect of cement content on the chloride penetration but also the effect of cement content on the chloride threshold value: the current results show that at lower cements content the penetration is reduced, which is a favorable effect; however, lower cement contents may result in lower threshold values if one considers the acceptable engineering approach whereby the threshold value is proportional to the cement content. In order to evaluate this combined influence of cement content, some calculations based on the LIFE 365 model [10] were carried out for 50 mm cover, assuming that the chloride threshold value is 0.2% by weight of cement and the surface chloride concentration is 2.5 kg/m^3 [8]. Diffusion coefficients were calculated from the Coulomb value using the relation published in [11]. The initiation times for the 0.45 concrete were 24.4, 22.2 and 32.0 years for mixtures with 450, 413 and 372 kg/m^3 of cement, respectively. Similar trends were obtained for the 0.52 *w/c* concrete. This clearly demonstrates the overall favorable effect of reducing the cement content using the water reducing admixtures applied in this study.

One would expect that the effect of the cement content on carbonation would be influenced similarly to the capillary absorption, as outlined and discussed above. Yet, carbonation was largely independent of the cement content and did not reduce at lower contents as obtained for capillary absorption and chloride penetration. A possible explanation to this trend is that the progress of carbonation front is influence by two factors: penetration of CO_2 and its reaction with $Ca(OH)_2$ to slow down its ingress. The reduction in cement content is expected to reduce the CO_2 penetration when considering its influence on reduction of capillary absorption (i.e. indication for a finer pore structure), yet the lower cement content will bind less CO_2. Perhaps the outcome of these two opposing effects is insensitivity of carbonation rates to cement content.

The trends reported here are similar in nature to those outlined by Buenfeld and Okundi [3] and Dhir et al. [6]. In their work they also suggested that in considering the influence of reducing cement content there is a need to take also into account its influence on the interfacial transition zone (ITZ). Lower cement content and higher aggregates content may lead to enhanced effect of the ITZ, to cause percolation when the content of aggregates is sufficiently high. In view of the effects of admixture resolved here, there is perhaps room to consider also the influence of the admixture on ITZ, with perhaps effects such as reduction in internal bleeding which may cause densification of the ITZ. Although the feasibility of the influence of the water reducing admixture was confirmed here, there is a need for a systematic and in-depth study to resolve such effects and verify such explanations.

4.2 Shrinkage

The results presented in Figs. 6 and 7 suggest that the overall influence of cement content on shrinkage is small, and no systematic trend of increase in shrinkage with increase in cement content could be seen. This is further demonstrated in Figs. 13 and 14: For similar cement content mixtures the shrinkage—weight loss curves are quite different, reflecting the influence of *w/c* (Fig. 13). Yet, the overall shrinkage strain was practically independent of *w/c* for the relevant concrete mixtures (Fig. 14), probably due to

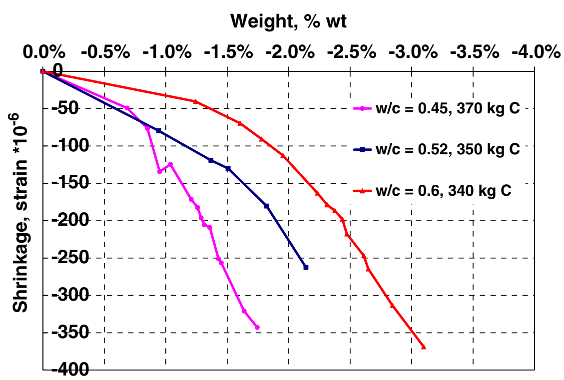


Fig. 13 Effect of *w/c* on shrinkage—weight loss curves of concretes having a roughly similar cement content of about 350 kg/m^3

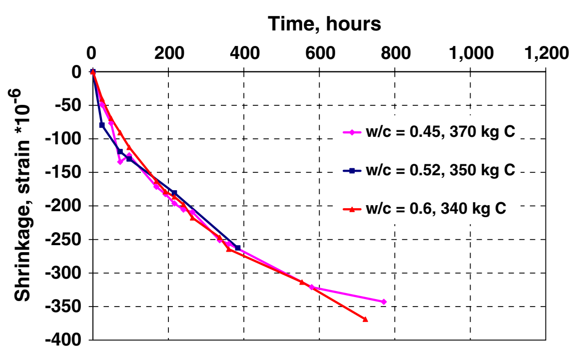


Fig. 14 Effect of *w/c* on shrinkage of concretes having a roughly similar cement content of about 350 kg/m^3

the relative reduction in paste volume as *w*/*c* increases (Fig. 12).

The small overall effect of cement content, and the fact that no systematic influence of cement content could be resolved to support the common notion that higher cement content is associated with greater shrinkage can perhaps be explained by the competition between several processes which somehow balance or mask each other:

- Increase in cement content to reduce *w*/*c* should lead to two competing process: reduction in *w*/*c* ratio should reduce shrinkage, while the increase in cement content (and paste content) should increase shrinkage [12].
- Reduction in cement content for a given *w*/*c* requires the formulation of the concrete with water reducing admixtures. The presence of the admixtures may result in an increase in the paste shrinkage due to modifications of the pore structure and surface tension. The feasibility for such an influence was demonstrated in this study (Figs. 8 and 9), but there is a need to resolve it more systematically, as well as explore the influence of the composition of the admixture.

5 Conclusions

The effect of cement content is different for the various properties of concretes and cannot be simply interpreted or predicted in terms of the paste content in the concrete. The broad observations on concrete properties were as follows:

1. Strength was a function of *w*/*c* and independent of cement content.
2. Total absorption which is an estimate of total porosity was proportional, as expected, to the paste content for a given *w*/*c*.
3. Capillary absorption and chloride ingress reduced with reduction in cement content for a given *w*/*c*, to an extent which was much greater than the reduction in total porosity. It was suggested that this trend might be due to the influences of the water reducing admixtures which are added to the lower cement content mixtures for the sake of workability, on modification of the pore structure, probably refining it.
4. The outcome of the combined effect of reduced chloride ingress at lower cement content and the reduced threshold chloride value was still favorable from corrosion performance point of view, as estimated by modeling of service life.
5. The carbonation was independent of cement content for a given *w*/*c*, and this was explained in terms of two competing processes, of reduction in penetration and reduction in CO_2 binding at lower cement contents.
6. The effect of cement content on shrinkage was relatively small and no trend for higher shrinkage with increased cement content could be established. Tests of pastes representing the paste phase in the concrete, suggest that the presence of water reducing admixture can lead to increase in shrinkage, thus counteracting the expected influence of reduction in shrinkage due to reduction in cement content for a given *w*/*c* ratio.
7. The current results are consistent with similar studies and suggest that the requirements for minimum cement content in standards should be revisited.

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References

1. Katz A, Baum H (2006) Effect of high level of fines content on concrete properties. ACI Mater J 103(6):474–482
2. Bentur A, Diamond S, Berke NS (1997) Steel corrosion in concrete. E&FN SPON, UK
3. Buenfeld NR, Okundi E (1998) Effect of cement content on transport in concrete. Mag Concr Res 50(4):339–351
4. Loo YH, Chin MS, Tam CT, Ong CGA (1994) A carbonation prediction model for accelerated carbonation testing of concrete. Mag Concr Res 46(168):191–200
5. Monteiro PJM, Helene PRL (1994) Designing concrete mixtures for desired mechanical properties and durability. In: Proceedings, concrete technology, past present and future, ACI proceedings SP-144, pp 191–200
6. Dhir RK, McCarthy MJ, Zhou S, Tittle PAJ (2003) Role of cement content in specifications for concrete durability: cement type influences. Struct Build 157(SB2):113–127. doi:10.1680/stbu.157.2.113.36479
7. Wasserman R, Bentur A (2006) Effect of concrete composition on durability in natural acidic environment. Adv Cement Res 18(4):135–143. doi:10.1680/adcr.2006.18.4.135
8. Wasserman R, Bentur A, Katz A (2007) Re-evaluation of the requirements in standards for minimum cement content

for durability performance. Research Report 2006640, National Building Research Institute, Technion, Haifa (in Hebrew)

9. EN 772-11 (2004–2006) Methods of test for masonry units—Part 11: Determination of water absorption of aggregate concrete, autoclaved aerated concrete, manufactured stone and natural stone masonry units due to capillary action and the initial rate of water absorption of clay masonry units (includes amendment A1:2004)
10. Thomas MDA, Bentz EC (2000) Computer program for predicting service life and life-cycle costs of reinforced concrete exposed to chlorides, University of Toronto. Life 365. http://www.nrmca.org/research/Life365.asp. Accessed 9 Oct 2008
11. Berke NS, Hicks MC (1992) The life cycle of reinforced concrete decks and marine piles using laboratory diffusion and corrosion data. In: Chaker V (ed) Corrosion forma and control for infrastructure. ASTM STP 1137, American Society for Testing and Materials, Philadelphia, pp 207–231
12. ACI 244R-01 (2001) Control of cracking in concrete structures. American Concrete Institute, Farmington Hills