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Effect of High Levels of Fines Content on Concrete Properties

by Amnon Katz and Hadassa Baum

The content of fines (particles smaller than 0.075 mm [No. 200] mesh) in aggregates used for the production of concrete is generally limited by most standards worldwide. In the current study, the effect of the addition of fines to normal-strength concrete at levels of up to 227 kg/m³ (383 lb/yd³) was studied in concrete mixtures prepared with constant workability.

It was found that as long as workability can be controlled by reasonable amounts of admixture, the addition of fines improves concrete strength by as much as 30%, somewhat reduces the carbonation rate, and slightly increases the volume changes of fresh and hardened concrete. When high dosages of admixture were required to maintain workability due to the presence of large amounts of ultra-fine particles (less than ~5 micron), properties of the concrete were seriously affected.

Keywords: aggregate; hardened concrete; workability.

INTRODUCTION

Fine aggregates (smaller than 4.75 mm, No. 4 mesh) play a very important role in controlling the properties of fresh concrete. They help to improve the cohesiveness of fresh concrete, improve its workability, and prevent segregation and bleeding.[1,2] However, the presence of very fine particles (smaller than 0.075 mm or minus No. 200 mesh), known as "fines," is generally limited for three reasons:

1. Particles of this size may lead to reduced workability due to the large surface area that must be wetted. This leads in turn to an increase in the amount of water required to maintain proper workability, to an increase in cement content required to maintain strength, and, as a result, to higher shrinkage values and greater sensitivity to cracking;[3]

2. Very fine particles tend to adhere to the surface of larger particles and prevent proper bonding between the cement paste and the aggregate.[4] The result is the formation of a weak aggregate-paste bond that promotes intensive cracking and weakens the concrete; and

3. Clay particles, which are smaller than a few microns, undergo significant volume changes when they absorb water and dry out thereafter. Wet clay particles, which expand in the fresh state of concrete, later shrink and, as a result, their presence may lead to large volume changes of the hardened concrete, increased sensitivity to cracking, ingress of deleterious substances, and reduced concrete strength.[5]

In view of these constraints, most standards limit the fines content to only a few percent. ASTM C 33[6] limits the fines content in fine aggregate to 3% in concrete subjected to abrasion and to 5% in all other kinds of concrete, as does the Israeli standard for concrete aggregates[7] (IS 3 1998). In the case of manufactured sand, however, which is made from crushed stone and is free of clay or shale, fines content can be increased to 5 and 7%, respectively. The European standard for aggregates[8] (EN 12620) allows four declared levels of fines content in fine aggregate (3, 10, 16, and 22%). Higher contents are allowed but they should be declared accurately. If, however, the fines content exceeds 3%, its harmfulness must be assessed using methods that determine the presence of clay in the fines. Additionally, specific limits can be established at different locations within the European community, according to local conditions. It appears that the authors of the standards realize that, in the case of manufactured sand, it is difficult to produce sand with very low fines content, although its effect on concrete is critical. Therefore, somewhat higher amounts of fines are allowed in manufactured sand, as long as it is free from clay and shale.

As a result of the aforementioned limitations, the fines are separated from the crushed stone by various techniques and dumped in landfill sites. The amount of waste fines that accumulate annually in the U.S. alone is in excess of 100 million tons.[9]

A new generation of concrete was developed in recent years, namely self-consolidating concrete (SCC). This type of concrete exhibits excellent workability, which allows free consolidation in the mold with minimal or no vibration. A key factor in manufacturing this concrete is the contribution of fines to the cohesiveness of the fresh mixture. A water to powder (cement + fines) ratio of ~1.0 is generally recommended, which yields fines content in the range of 100 to 300 kg/m³ (170 to 505 lb/yd³). Very large volumes of fines are incorporated into the mixture without showing any detrimental effect.[10] Thus, one may conclude that large amount of fines can also be used in normal slump concrete. On the other hand, another work[11] recently tested the effect of the addition of fines to concrete. It was found that the addition of a small amount of fines (~55 kg/m³ [93 lb/yd³]) led to a significant reduction in the workability of the fresh concrete and to some increase in its compressive strength. Not all water-reducing agents tested in the said study[11] managed to cope with the slump loss. However, the composition (size distribution and mineralogy) of the fines tested in the study was not clear; therefore, the affecting parameters could not be identified.

RESEARCH SIGNIFICANCE

It appears that it is possible to incorporate a large amount of fines into normal slump concrete, without damaging other concrete properties, using modern water-reducing agents. The objective of the present work was to systematically study the effect of fines on the properties of the most widely-manufactured concrete (normal-strength concrete with slump of ~130 mm, prepared under normal conditions), with fines content as high as 227 kg/m³ (383 lb/yd³). Positive results of this study will enable the use of larger amounts of fines in the manufactured sand, reducing the environmental impact and direct costs involved in its removal from the sand.

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EXPERIMENTAL PROGRAM

The variables studied in this work were particle size (fineness) of fines, their content, and the method applied to adjust the required workability due to their presence.

The effect of fines on early-age and later-age properties was evaluated. The early-age study included workability, slump loss, air content and plastic shrinkage cracking, whereas the hardened (late-age) concrete properties studied were strength development, drying shrinkage, and durability (carbonation resistance).

Three types of fines were evaluated with median particle size of 28, 19, and 8 μm, denoted as Fines 28, 19, and 8, respectively. Concrete mixtures with up to approximately 200 kg fines per m^3 concrete (337 lb/yd^3), at 40 kg/m^3 (67 lb/yd^3) increments, were studied. It should be noted that the crushed aggregates used in this study already contain some amount of fines (~27 kg/m^3 [45 lb/yd^3]), and the following results will refer only to the additional fines added according to the experimental program. The maximum fines content relative to the total amount of fine aggregates was ~21%.

Series I, II, and III comprised concretes with varying content of Fines 28, 19, and 8, respectively. The workability of the mixtures was adjusted by adding a high-range water-reducing admixture (HRWRA) to compensate for the increase in water demand resulting from the higher fines content. In Series IV, 19 μm fines were used (as in Series II), but the adjustment for workability was obtained by increasing the water content and consequently also the cement content. The water-cement ratio (*w/c*) in all the mixtures was kept constant at 0.62. Workability of the fresh mixtures for all test series was adjusted to a slump value of 135 ± 15 mm (5.5 ± 0.5 in.). One control mixture, containing no fines, was prepared for all series. Table 1 presents a summary of the experimental program and Table 2 lists the composition of all 20 mixtures.

Table 1—Summary of experimental program

	Type of fines	Means of slump control	Fines content
Series I	Fines 28	HRWRA	0 to 200 kg/m^3 at 40 kg/m^3 (0 to 337 lb/yd^3 at 67 lb/yd^3) increments*
Series II	Fines 19	HRWRA	
Series III	Fines 8	HRWRA	
Series IV	Fines 19	Cement paste (increase in cement and water)	

*0 to 160 kg/m^3 (0 to 270 lb/yd^3) only in Series III.
Note: HRWRA = high-range water-reducing admixture.

Materials

Aggregates—Coarse aggregate (9.5 to 25.0 mm [3/8 to 1 in.]) was prepared from crushed dolomite stone, with an absorption of ~0.8% and fines content lower than 1%. The fine aggregate consisted of natural siliceous sand (NS) and two types of manufactured sand (MS-I and MS-II). MS-I was made from pre-washed crushed dolomite stone; however, not all the fines were removed by washing and the residual fines content after washing was approximately 4.9%. MS-II was made from limestone containing a significant amount of fines (31%). This fraction of fines served as Fines 8 (as

Table 2—Mixture composition of all experiment series, kg/m^3 (lb/yd^3)*

	Designation	Cement	Water	Coarse	MS-I	MS-II	NS	Fines	HRWRA	Final slump, mm (in.)	Air content, %
Control	REF	278 (469)	173 (292)	872 (1470)	563 (949)	—	525 (885)	0	0.56 (0.9)	140 (5.5)	2.1
Series I (Fines 28)	I/40	276 (465)	172 (290)	867 (1461)	560 (944)	—	483 (814)	41 (69)	1.11 (1.9)	140 (5.5)	3.1
	I/80	276 (465)	172 (290)	866 (1460)	559 (942)	—	444 (748)	81 (137)	1.38 (2.3)	150 (6.0)	3.5
	I/120	276 (465)	172 (290)	867 (1461)	560 (944)	—	408 (688)	122 (206)	1.38 (2.3)	140 (5.5)	3.0
	I/160	275 (463)	172 (290)	863 (1455)	558 (941)	—	367 (619)	163 (275)	2.20 (3.7)	125 (5.0)	3.1
	I/200	275 (463)	173 (292)	871 (1468)	562 (947)	—	328 (553)	205 (346)	3.89 (6.5)	145 (5.7)	3.1
Series II (Fines 19)	II/40	276 (465)	172 (290)	871 (1468)	559 (942)	—	481 (811)	41 (69)	1.10 (1.8)	150 (6.0)	2.8
	II/80	278 (469)	173 (292)	871 (1468)	562 (947)	—	445 (750)	82 (138)	1.11 (1.8)	125 (5.0)	2.5
	II/120	276 (465)	172 (290)	868 (1463)	559 (942)	—	401 (676)	122 (206)	2.21 (3.7)	125 (5.0)	3.2
	II/160	276 (465)	172 (290)	868 (1463)	559 (942)	—	359 (605)	163 (275)	3.31 (5.5)	125 (5.0)	3.3
	II/200	288 (485)	180 (303)	902 (1520)	583 (983)	—	322 (543)	212 (357)	7.48 (12.6)	125 (5.0)	3.9
Series III (Fines 8)	III/40	271 (457)	169 (285)	850 (1432)	487 (821)	97 (163)	472 (796)	40 (67)†	2.74 (4.6)	140 (5.5)	5.2
	III/80	268 (451)	167 (281)	841 (1418)	420 (708)	192 (324)	427 (720)	80 (135)†	3.79 (6.3)	130 (5.1)	7.5
	III/120	257 (433)	160 (270)	806 (1359)	344 (580)	275 (464)	372 (627)	120 (202)†	7.78 (13.1)	130 (5.1)	>12.0
	III/160	256 (432)	159 (268)	804 (1355)	284 (479)	366 (617)	333 (561)	160 (270)†	12.3 (20.7)	90 (3.5)	>12.0
Series IV (Fines 19)	IV/40	292 (492)	182 (307)	856 (1443)	553 (932)	—	478 (806)	40 (67)	0.55 (0.9)	125 (5.0)	2.1
	IV/80	295 (497)	184 (310)	854 (1439)	551 (929)	—	438 (738)	80 (135)	0.54 (0.9)	130 (5.1)	2.2
	IV/120	316 (533)	197 (332)	832 (1402)	537 (905)	—	390 (657)	117 (197)	0.53 (0.9)	120 (4.7)	2.2
	IV/160	332 (560)	206 (347)	821 (1384)	530 (893)	—	349 (588)	155 (261)	0.52 (0.9)	120 (4.7)	1.9
	IV/200	353 (595)	219 (369)	799 (1347)	516 (870)	—	305 (514)	188 (317)	0.51 (0.9)	130 (5.1)	2.0

*Aggregates in SSD condition, water quantities were adjusted before mixing.
†Fines in Series III compose the fine fraction of MS-II.
Note: HRWRA = high-range water-reducing admixture.

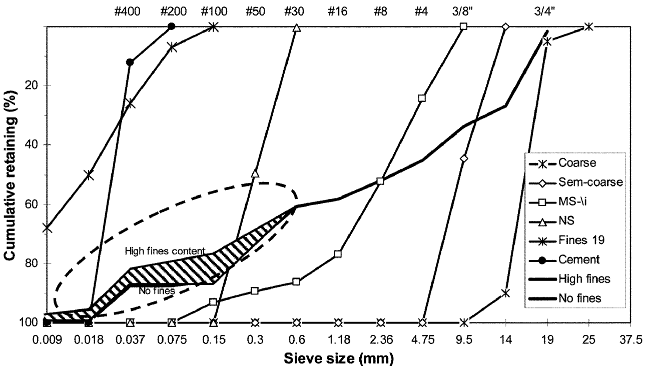

Fig. 1—Sieve analysis of tested aggregates, including Fines 19, cement, and their mixture limits.

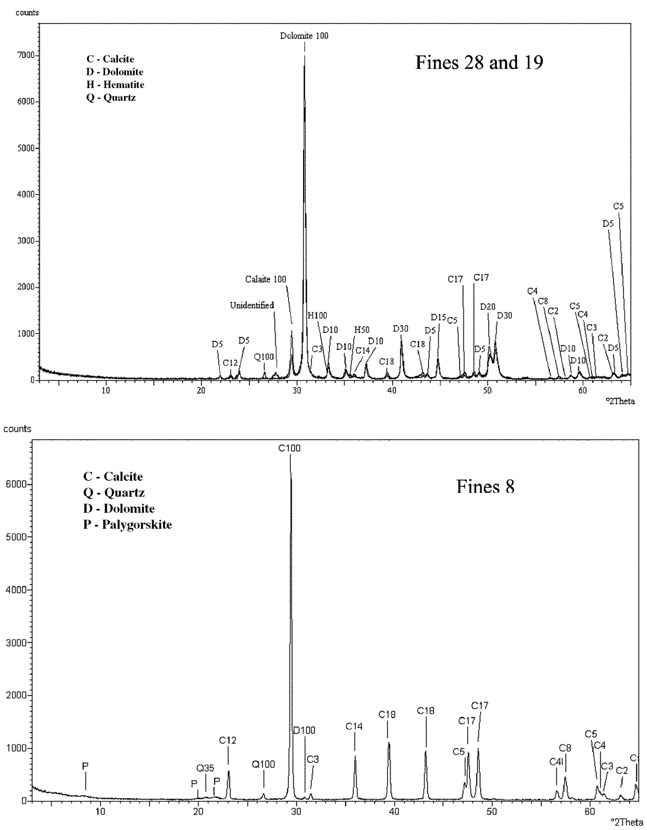

Fig. 2—X-ray diffraction of fines.

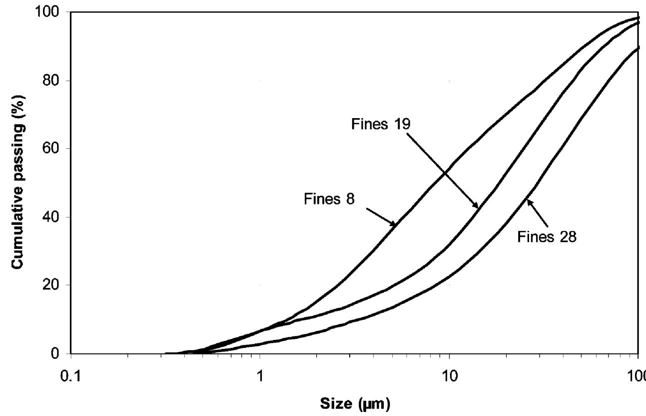

Fig. 3—Particle size distribution of fines.

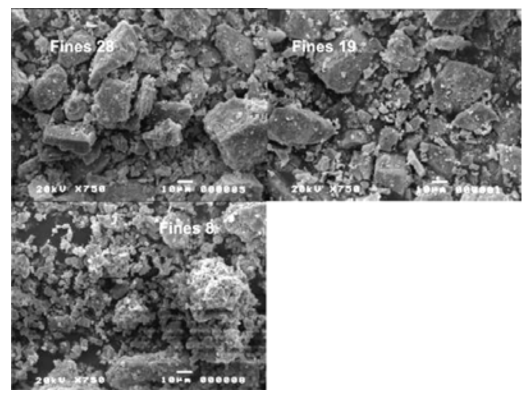

Fig. 4—SEM images of fines.

Table 3—Properties of tested aggregates

Aggregate type	Fineness modulus	Absorption, %	Specific gravity	Median particle size, µm
Coarse	6.9	0.8	2.74	—
Manufactured sand (MS-I)	4.2	0.9	2.74	—
Manufactured sand (MS-II)	2.8	4.6	2.45	—
Natural sand (NS)	1.5	0.1	2.63	—
Fines 28	—	—	2.79	28
Fines 19	—	—	2.80	19
Fines 8	—	—	2.64	8

follows). Table 3 presents a summary of aggregate properties and Fig. 1 presents aggregate grading on a scale extended to include the fine particles (fines and cement).

Fines—Fines from three sources were used, all of which were derived from crushed stone. Fines 28 and 19 were taken from the separation process of asphalt plants at two different locations and quarries. The same aggregate was used in these plants for the production of ordinary concrete and asphalt concrete, thus these fines represent the fines that normally exist in the aggregates from these quarries. The mineral composition of the two fines, as determined by x-ray diffraction (XRD), showed a mixture of dolomite and some calcite at both locations, with traces of quartz in Fines 28 and traces of hematite in Fines 19 (Fig. 2). Fines 19 contained slightly more calcite than did Fines 28. Size distribution of the fines, as determined by laser diffraction (Fig. 3), showed a median size of 28 and 19 µm for Fines 28 and 19, respectively. Scanning electron microscopy (SEM) images (Fig. 4) showed the angular nature and the size distribution of these fines. The third type of fines, Fines 8, was the small fraction of MS-II, as mentioned previously. X-ray diffraction of Fines 8 showed mainly calcite with possible traces of clay (less than 1%) (Fig. 2). Examination of the size distribution of Fines 8 (Fig. 3) showed a finer material compared with the other fines, with a median size of 8 µm.

Fines 28 and 19 were added to the mixture separately, according to the experimental program, whereas Fines 8 was added as part of MS-II, that is, the total amount of MS-II in the mixture was determined according to the planned amount of Fines 8 that makes up approximately 1/3 of MS-II. The other fraction of MS-II (the larger particles) replaced an equal amount of manufactured sand MS-I in the mixture.

Cement—The cement used was CEM II /A-V 42.5N according to EN 197-1,[12] similar to ASTM Type I(PM) (ASTM C 595[13]). Table 4 presents the chemical analysis of the cement.

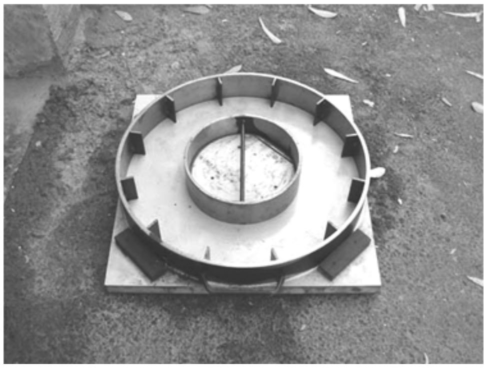

Fig. 5—Apparatus for detecting plastic shrinkage cracking.

Admixture—An HRWRA was used at variable dosages, according to the experimental program. The HRWRA selected exhibited a certain retarding effect and conformed to ASTM C 494, Types A and F.

Mixing and testing

All of the experiments were performed in a climate-controlled room at 20 °C (68 °F) and 55% relative humidity (RH). Coarse aggregate was added to a pre-wetted free-fall mixer, together with 2/3 of the water, and mixed for 1 minute. The mixer was then covered and left for 5 minutes to allow the dry aggregates to absorb the water. All types of fine materials were then added (cement, MS, NS and fines), together with the rest of the water and HRWRA, and the mixture was mixed for an additional 10 minutes.

Workability of the fresh mixture was determined by the slump test according to ASTM C 143.[14] Workability was then adjusted according to the experimental program, followed by additional mixing for ~5 minutes.

The following properties of the fresh concrete were measured:

- Air content was determined according to ASTM C 231.[15]
- Unit weight was measured according to ASTM C 138.[16]
- Slump loss was measured on mixtures with fines content of 0, 40, 120, and 200 kg/m^3 (0, 67, 202, and 337 lb/yd^3) as follows: After achieving the planned slump and removing some concrete for the preparation of specimens for hardened concrete tests (approximately 1/3 of the batch), mixing continued, and slump was measured every 20 minutes until the slump reduced to zero. Slump loss was measured for Series I, II, and IV only.
- Plastic shrinkage cracking was tested on mixtures with fines content of 0, 80, 160, and 200 kg/m^3 (0, 135, 270, and 337 lb/yd^3), using 80 mm-thick (3.15 in.) rings with internal and external diameters of 280 and 580 mm (11.0 and 22.8 in.), respectively (Fig. 5), as described by Reference 17. Two ring specimens of fresh concrete were placed in a wind tunnel and hot, dry air (30 °C [86 °F] and 30% RH) was blown over the surface of the concrete in the rings. Concrete surface was inspected 24 hours after mixing. The results of this test are not absolute values, but they can serve as a basis for comparison between different mixtures.

Tests performed on hardened concrete

- Compressive strength was measured on 100 mm (3.9 in.) cubes that were stored in a moist room for the first 7 days (21 °C [70 °F]) and 100% RH) and in laboratory air (21 °C [70 °F]) and 55% RH) thereafter, until the testing day. Compressive strength was tested at 2, 7, 28, and 90 days.

Table 4—Chemical analysis of cement (% weight)

CaO	57.73
SiO_2	18.46
Al_2O_3	5.93
Fe_2O_3	3.37
MgO	1.15
TiO_2	0.42
K_2O	0.37
Na_2O	0.21
P_2O_5	0.48
Mn_2O_3	0.04
SO_3	2.42
Cl	0.02
IR	3.97
FL	1.60

- Drying shrinkage was tested on 70 x 70 x 280 mm (2.8 x 2.8 x 11.0 in.) prisms in accordance with ASTM C 157[18] following 7 days of water curing and drying in the laboratory air (21 °C [70 °F]) and 55% RH).
- Carbonation was tested on 70 x 70 x 280 mm (2.8 x 2.8 x 11.0 in.) prisms. Specimens were stored in water for 7 days, followed by 21 days of exposure to laboratory air. At 28 days, the specimens were split and tested for depth of carbonation using a phenolphthalein solution. Then, the faces at both ends of the prisms were sealed and the specimens were stored in a carbonation chamber with a high concentration of CO_2 (5% of CO_2, 30 °C [86 °F]) and 50% RH). The specimens were split and tested periodically for depth of carbonation, until carbonation reached the full depth of the specimen. The results of tests on hardened concrete represent the average of at least three tests.

RESULTS AND DISCUSSION

Fresh concrete

Workability—Increasing the fines content increased the amount of HRWRA needed to maintain a constant slump, or alternatively, the amount of cement paste (amount of water), as seen in Table 2. In Series I and II, in which the slump was controlled by varying HRWRA contents, increasing the amount of fines from 0 to 120 and 200 kg/m^3 (0 to 202 and 337 lb/yd^3) increased the admixture demand as follows: In Series I, from 0.56 kg/m^3 (0.94 lb/yd^3) to 1.38 and 3.89 kg/m^3 (2.33 and 6.56 lb/yd^3), respectively; and in Series II, from 0.56 kg/m^3 (0.94 lb/yd^3) to 2.21 and 7.48 kg/m^3 (3.73 and 12.61 lb/yd^3), respectively (Fig. 6). In Series III, the admixture demand was significantly higher: 3.79 kg/m^3 (6.39 lb/yd^3) and 12.3 kg/m^3 (20.73 lb/yd^3) of admixture were needed for fines contents of 80 kg/m^3 (135 lb/yd^3) and 160 kg/m^3 (270 lb/yd^3), respectively. With such a high admixture demand, it was not realistic to prepare a mixture with 200 kg/m^3 (337 lb/yd^3) of fines in Series III. In Series IV, the water demand increased from 173 kg/m^3 (292 lb/yd^3) to 197 and 219 kg/m^3 (332 and 369 lb/yd^3), respectively.

It seems that the fineness of the fines had a strong impact on the admixture demand. The median size of Fines 19 was smaller than that of Fines 28 and, accordingly, the admixture demand was almost double for Fines 19 mixtures in which the fines content was highest. When Fines 8 was used, the admixture content increased rapidly with the fines content,

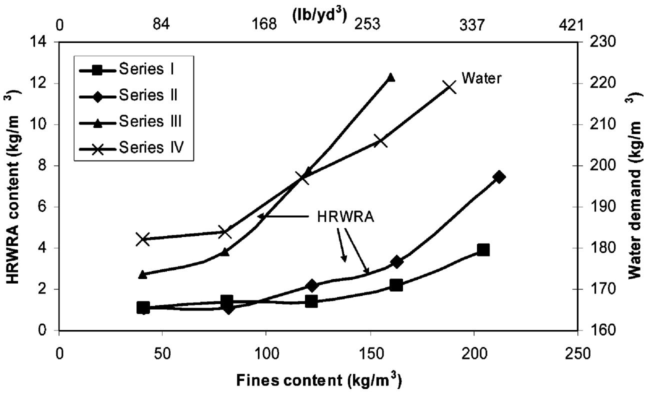

Fig. 6—Effect of fines on admixtures and water demand required for constant slump (1 kg/m^3 = 1.69 lb/yd^3).

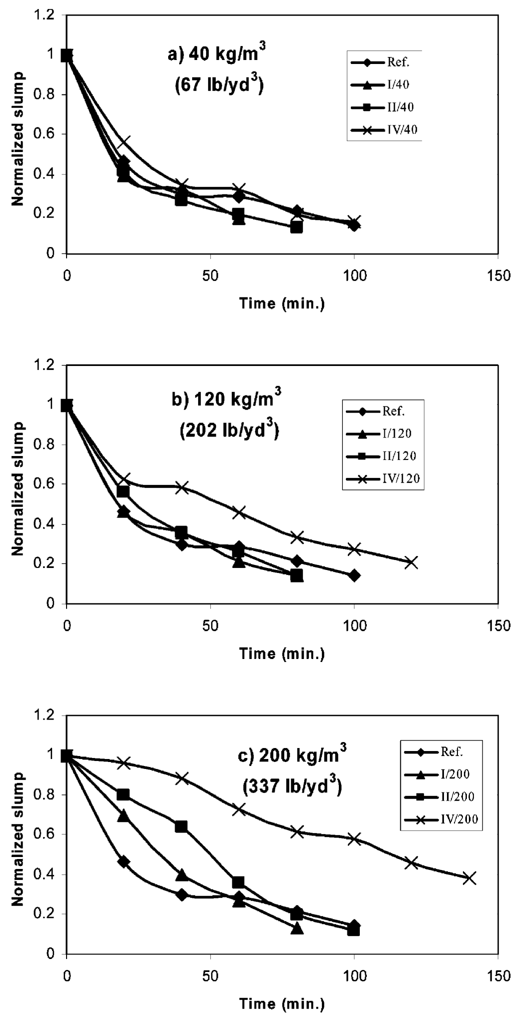

Fig. 7—Slump loss over time for various mixtures.

and reached levels that had a detrimental effect on the concrete. In all the mixtures, the increase in HRWRA or water was nonlinear, with the increase becoming particularly high at the higher levels of fines (Fig. 5). This behavior suggests that each type of fines will reach a practical upper limit of admixture addition that will limit the fines content.

It is possible that the newest generation of HRWRA will be more successful in coping with the high content of very fine material, as found in special concretes such as reactive powder concrete (RPC). This issue, however, requires further investigation.

Air content—Increasing the amount of HRWRA seemed to affect the air content, whereas altering the workability by controlling the paste content had no such affect (Table 2). It seems that fines content by itself had no effect on the air content and the only influence seen was that due to the admixture. In Series I and II, air content increased from 2 to ~3% as the amount of admixture became significant (the initial amount of admixture in the control mixture, 0.2% of the cement content, was almost negligible), but no clear relationship can be seen between the admixture content and the degree of air entrainment. The extremely high admixture content in Series III led to a very high degree of air entrainment, which exceeded 12%, the upper limit of the measuring device.

The air content in Series IV was ~2.0% for all fines content, indicating that the increased air in the other mixtures was probably a result of the increased admixture content and not a direct result of the increased fines content.

Slump loss—The effect of time on the normalized slump loss is presented in Fig. 7 for Series I, II, and IV at fines content of 40, 120, and 200 kg/m^3 (67, 202, and 337 lb/yd^3). The initial slump for each mixture was adjusted to 135 ± 15 mm (5.5 ± 0.5 in.), and the results presented are normalized to that initial slump. It appears that up to a level of 120 kg/m^3 (202 lb/yd^3), no significant difference exists between Series I and II and the control mixture without fines addition, despite the enlarged dosage of HRWRA (Fig. 7(a) and (b)). Series IV, in which the slump was adjusted by adding water, exhibited a more moderate loss of slump. A similar trend was seen at higher levels of fines (200 kg/m^3 [337 lb/yd^3]): The slump loss of Series IV was much more moderate than in other mixtures, and that of Series I and II was slightly more moderate than that of the control mixture (Fig. 7(c)).

The governing parameter affecting the slump loss seems to be the admixture's characteristics, mainly, its time-dependent properties. In the mixtures in which higher workability was achieved by the addition of HRWRA, the slump decreased more rapidly compared with mixtures in which workability was achieved by adding water. In Series IV, for example, which contained 200 kg/m^3 (337 lb/yd^3) of fines, the workability was adjusted by adding only water (and cement). Thus, slump loss was much more moderate than for the mixtures in Series I or II, in which the slump was adjusted by adding admixture with a limited time effect (Fig. 7(c)). It should be noted that in Mixture IV/200, the amount of cement increased by 27% whereas the amount of HRWRA remained constant, leading to a lower concentration of admixture relative to the cement content.

A secondary effect is probably the admixture's retarding effect: Rapid slump loss was observed in the control mixture, and it became somewhat slower with the increase in admixture dosage in Series I and II. Series IV is different, as its slump loss is much slower, despite the smaller amounts of admixture. This is, however, the result of the major effect discussed previously and not the result of the retarding effect, which is only secondary.

Plastic shrinkage cracking—Table 5 presents results of early-age shrinkage as the sum of the two rings tested. No cracks developed in the control mixture, whereas various extents of cracking developed in the mixtures that contained fines. Figure 8 presents an example of cracking in mixture IV/160. Very few fine cracks developed in Series II, whereas many very fine and short cracks developed in Series I. No significant relationship between fines content and the

Table 5—Cracking pattern due to plastic shrinkage

		Sum of two rings	
		No. of cracks	Width, mm (in.)
Control	REF	None	—
Series I	I/80	Many	0.05 to 0.10 (0.002 to 0.004)
	I/160	Many	0.03 to 0.10 (0.001 to 0.004)
	I/200	Many	0.06 to 0.10 (0.002 to 0.004)
Series II	II/80	9	0.05 (0.002)
	II/160	3	0.05 (0.002)
	II/200	2	0.05 (0.002)
Series III	III/40	3	0.05 (0.002)
	III/80	1	0.10 (0.004)
	III/160	19	0.10 to 0.60 (0.004 to 0.024)
Series IV	IV/80	8	0.05 to 0.15 (0.002 to 0.006)
	IV/160	10	0.05 to 0.20 (0.002 to 0.008)
	IV/200	11	0.05 to 0.20 (0.002 to 0.008)

number, width, or length of the cracks was seen in any of these mixtures. It is possible that the large number of very fine cracks in Series I mixtures could be a result of surface crazing of the specimens due to a greater extent of bleeding, which was not tested in this study.

Series III exhibited the maximal sensitivity to fines content. In its maximal fines content of 160 kg/m^3 (270 lb/yd^3), a large number of cracks (19) appeared with widths of up to 0.6 mm (0.023 in.). Mixture III/160, of all mixtures, is the mixture that practically measured plastic shrinkage throughout the entire test duration, thus leading to higher plastic shrinkage values. Strength results, discussed in the following, indicated that no strength was gained during the first 2 days (probably due to the very high dosage of HRWRA, as discussed previously). This mixture was therefore in a plastic state throughout the entire 24 hours of the test, whereas other mixtures were in the plastic state for a limited time only, that is, until setting began.

A moderate increase in both the number of cracks and their widths was seen in Series IV, with the increase in fines content. When the fines content was increased from 80 to 200 kg/m^3 (135 to 337 lb/yd^3), the number of cracks increased from 8 to 11 and their widths increased from the range of 0.05 to 0.15 mm (0.002 to 0.006 in.) to the range of 0.05 to 0.2 mm (0.002 to 0.008 in.). Water content in this series increased with the fines content, leading probably to a greater sensitivity to early-age volume changes, although differences between mixtures with various fines loads are relatively small.

Hardened concrete

Compressive strength—Most of the mixtures exhibited an increase of up to 30% in their compressive strength as a result of the addition of fines (Table 6). Some improvement was seen for the addition of a small amount of fines (40 kg/m^3 [67 lb/yd^3]), and this improvement increased with the increase in the amount of fines added. Maximum improvement was generally seen at age 28 days. Figure 9 presents the compressive strength at 28 days relative to the control mixture. An improvement of more than 10% was seen for small additions of fines (40 kg/m^3 [67 lb/yd^3]) in all series. At a fines content of 200 kg/m^3 (337 lb/yd^3), the improvement was ~30% for Series I and II and a mere 17% for Series IV. Mixtures in Series III exhibited strength reduction as the fines content increased beyond 80 kg/m^3 (135 lb/yd^3).

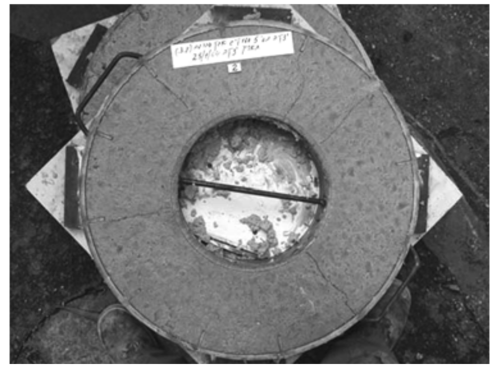

Fig. 8—Early-age cracking of Mixture IV/160.

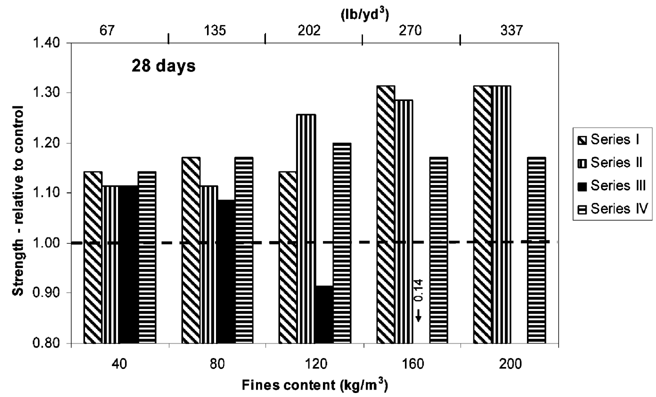

Fig. 9—Compressive strength at 28 days relative to control mixture.

The detrimental effect of fines in Series III was already seen in the properties of the fresh mixture, and it affected the properties of the hardened mixture as well. Some improvement was seen in Series III when 40 kg/m^3 (67 lb/yd^3) of fines were added, but the strength decreased significantly with the increase in fines content due to the cumulative effect of fines and admixture.

Proper dispersion of fines is an essential parameter required to guarantee the proper contribution of fines to the strength of the mixture. This can be seen in the differences between Series IV and Series I and II. Water is not as efficient in the dispersion of fines as is HRWRA; thus, the contribution of fines to strength in Series IV was smaller compared with the other series. This statement is valid, however, only as long as other deleterious properties of the admixture, such as air entrainment or retarding, do not damage concrete properties.

In addition to the absolute strength, strength development should be considered as well. Figure 10 presents the development of strength from age 2 to 90 days for Series I, IV, and the control mixture relative to their 28-day strengths. It seems that mixtures containing large amounts of fines, in which workability was compensated by adding admixture, showed a smaller relative strength at 2 days, but this gap was closed later on. This reflects perhaps the retarding effect of the HRWRA when added in a high dose. Unlike pozzolanic materials, in which a slow pozzolanic reaction leads to significant strength gain beyond the nominal age of 28 days, the main contribution of fines to the strength is exhibited up to this age, with negligible strength gain thereafter.

In Series IV, in which the paste content increased with the fines content rather than the admixture content, the development

Table 6—Development of compressive strength in all mixtures

		Compressive strength, MPa (ksi)*				Strength—relative to control			
Series	Mixture no.	2 days	7 days	28 days	90 days	2 days	7 days	28 days	90 days
Control	REF	13 (1.9) 4.6%	23 (3.3) 3.0%	35 (5.1) 4.0%	38 (5.5) 4.7%	1.00	1.00	1.00	1.00
Series I	I/40	13 (1.9) 3.8%	24 (3.5) 2.5%	40 (5.8) 1.5%	42 (6.1) 3.1%	1.00	1.04	1.14	1.11
	I/80	14 (2.0) 2.9%	25 (3.6) 1.6%	41 (5.9) 2.2%	42 (6.1) 2.1%	1.08	1.09	1.17	1.11
	I/120	14 (2.0) 2.5%	26 (3.8) 2.3%	40 (5.8) 3.2%	42 (6.1) 1.7%	1.08	1.13	1.14	1.11
	I/160	14 (2.0) 1.4%	29 (4.2) 2.1%	46 (6.7) 0.4%	46 (6.7) 0.6%	1.08	1.26	1.31	1.21
	I/200	11 (1.6) 9.9%	29 (4.2) 3.7%	46 (6.7) 3.3%	46 (6.7) 4.1%	0.85	1.26	1.31	1.21
Series II	II/40	14 (2.0) 0.7%	24 (3.5) 2.1%	39 (5.7) 1.8%	41 (5.9) 2.4%	1.08	1.04	1.11	1.08
	II/80	14 (2.0) 2.9%	25 (3.6) 2.0%	39 (5.7) 2.6%	41 (5.9) 0.2%	1.08	1.09	1.11	1.08
	II/120	13 (1.9) 1.5%	28 (4.1) 1.1%	44 (6.4) 2.5%	46 (6.7) 1.7%	1.00	1.22	1.26	1.21
	II/160	12 (1.7) 0.8%	27 (3.9) 1.9%	45 (6.5) 2.7%	46 (6.7) 3.7%	0.92	1.17	1.29	1.21
	II/200	0	26 (3.8) 2.3%	46 (6.7) 3.7%	45 (6.5) 7.1%	0.00	1.13	1.31	1.18
Series III	III/40	12 (1.7) 1.7%	24 (3.5) 1.2%	39 (5.7) 2.6%	39 (5.7) 1.5%	0.92	1.04	1.11	1.03
	III/80	9 (1.3) 6.7%	24 (3.5) 5.8%	38 (5.5) 1.1%	38 (5.5) 1.8%	0.69	1.04	1.09	1.00
	III/120	0	17 (2.5) 3.5%	32 (4.6) 5.3%	31 (4.5) 2.3%	0.00	0.74	0.91	0.82
	III/160	0	0	5 (0.7) 4.0%	5 (0.7) 2.0%	0.00	0.00	0.14	0.13
	III/200	—	—	—	—	—	—	—	—
Series IV	IV/40	16 (2.3) 2.5%	26 (3.8) 1.9%	40 (5.8) 1.0%	43 (6.2) 2.8%	1.23	1.13	1.14	1.13
	IV/80	15 (2.2) 4.7%	27 (3.9) 0.7%	41 (5.9) 2.2%	44 (6.4) 0.9%	1.15	1.17	1.17	1.16
	IV/120	15 (2.2) 4.7%	28 (4.1) 1.1%	42 (6.1) 1.9%	45 (6.5) 1.8%	1.15	1.22	1.20	1.18
	IV/160	15 (2.2) 1.3%	26 (3.8) 1.5%	41 (5.9) 0.7%	45 (6.5) 0.7%	1.15	1.13	1.17	1.18
	IV/200	15 (2.2) 4.7%	26 (3.8) 3.5%	41 (5.9) 1.0%	45 (6.5) 2.9%	1.15	1.13	1.17	1.18

*Standard deviation is expressed as percent of strength.

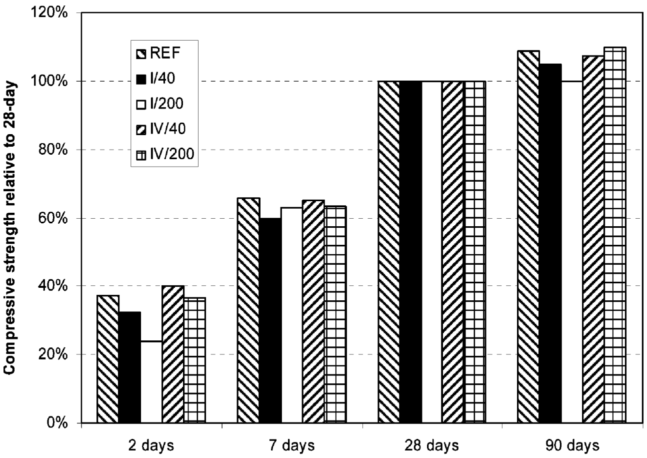

Fig. 10—Development of compressive strength for control and Series I and IV relative to their 28-day strength.

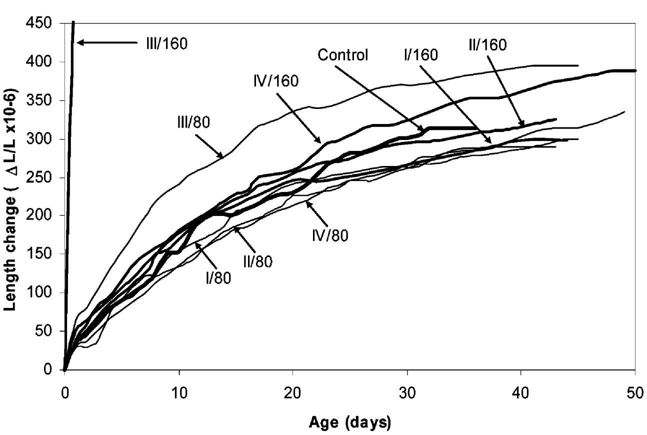

Fig. 11—Development of drying shrinkage.

of strength was more similar to that of the control regardless of the fines content.

Improved grading of the mixture at the ultra-fine level, that is, particles smaller than the cement grain size (smaller than a few microns), probably lead to better packing of the mixtures, which, together with additional nucleation sites for the hydration products, lead to the formation of a denser matrix and to improved strength.[19,20] Contribution of fines to the strength was most significant at 28 days with no strength gain thereafter, indicating that a filler effect is more likely.

Drying shrinkage—The initial rate of shrinkage and the final shrinkage were evaluated for the various series (Table 7). Typical development of drying shrinkage is presented in Fig. 11. Mixtures from Series I and II exhibited similar final shrinkage of approximately 310×10^{-6} m/m regardless of fines content. In Series III, a significant increase in final shrinkage was observed with the increase in fines content (Fig. 11); at already low fines content, shrinkage increased by ~25%. At a high fines content of 160 kg/m^3 (270 lb/yd^3), the extent of shrinkage was approximately three times that of the control. It seems that the extremely high shrinkage values of the latter are associated with their negligible strength observed at age 7 days, at which the shrinkage test began. The high porosity of this series together with very low strength leads to extremely higher shrinkage values compared with the other mixtures, and particularly to increased shrinkage during the first 2 days of exposure.

The final shrinkage in Series IV increased with the increase in fines content by up to ~30%, with most of the change occurring as a result of the increase in fines content of up to 120 kg/m^3 (202 lb/yd^3). Increased shrinkage is expected when the amount of paste increases, resulting from the increased water demand in this series.

The initial shrinkage rate, at which most of the shrinkage occurs, was quite similar for all mixtures, except those from

Table 7—Rate of drying shrinkage during first 10 days and final shrinkage

Series	Mixture no.	Initial rate ($\times 10^{-6}$ strain/day)	Final ($\times 10^{-6}$ strain)
Control	REF	14	314
Series I	I/40	14	335
	I/80	14	289
	I/120	12	287
	I/160	14	298
	I/200	15	350
Series II	II/40	16	306
	II/80	15	299
	II/120	15	325
	II/160	16	325
	II/200	18	301
Series III	III/40	18	342
	III/80	22	395
	III/120	23	388
	III/160	37	914
	III/200	—	—
Series IV	IV/40	12	312
	IV/80	12	336
	IV/120	14	413
	IV/160	16	389
	IV/200	14	357

Series III (Table 7). In Series III, the initial rate of shrinkage increased, with the increase in the amount of fines: a small addition of 40 kg/m^3 (67 lb/yd^3) fines, led to a ~30% increase in the initial rate of shrinkage and to a 10% increase in the final shrinkage. This effect continued to grow with the increase in fines content. It should be noted that Mixtures III/40 and III/80 exhibited improved compressive strength despite the increased shrinkage.

Carbonation—Depth of carbonation after 28 days of exposure to accelerated conditions is shown in Fig. 12 for all mixtures. Within the accuracy limitations of this method (approximate error ±1 mm [0.039 in.]), it can be said that Series I and II exhibited slightly reduced carbonation depth at moderately increased fines content, but this contribution ceased when high levels of fines were used. When slump reduction was compensated for by adding cement paste, however, the carbonation depth clearly decreased with the increase in fines content. It appears that increasing the paste content in the mixture leads to improved performance, which correlates well with the recommendations of the European Standard for concrete (EN 206), which calls for an increase in the cement content as the environment becomes more aggressive.

Of special interest are the results observed for Series III. Increasing the fines content in Series III clearly increased the carbonation depth. At a fines content of 160 kg/m^3 (270 lb/yd^3), the natural carbonation before starting the accelerated carbonation test was 9 mm (0.35 in.) compared with approximately 2 mm (0.08 in.) for mixtures of the other series. In this mixture, full-depth carbonation was obtained after only 2 days of exposure to the accelerated conditions. This might be expected and is probably associated with the reduced strength observed for this mixture and its presumably high porosity. The results, however, indicate increased carbonation depth also for mixtures that contained only small amounts of fines (40 and 80 kg/m^3 [67 and 135 lb/yd^3]) but exhibited better strength performance.

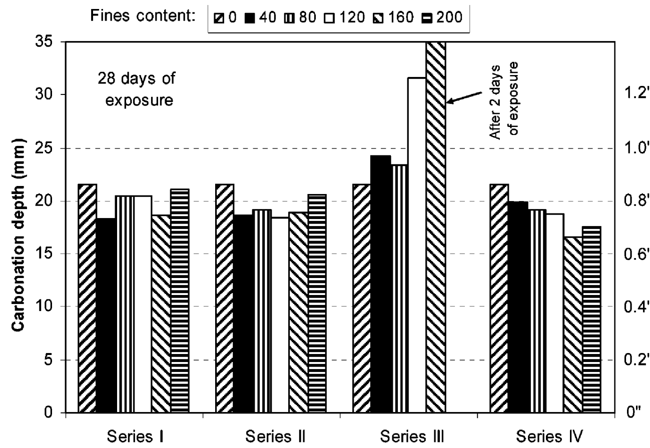

Fig. 12—Carbonation depth after 28 days of exposure to accelerated carbonation condition.

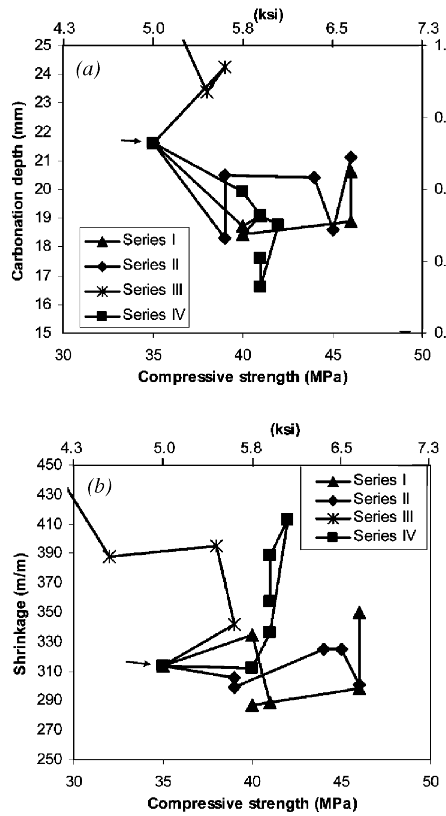

Fig. 13—Strength-carbonation: (a) strength shrinkage; and (b) relationships.

Strength-durability relationships—The relation between strength and durability in the mixtures investigated herein is not straightforward, as is for normal concrete, because considerable differences in performance were observed for mixtures having the same *w/c* and strength. To explore these characteristics, the properties of the studied mixtures were evaluated through the carbonation-strength or shrinkage-strength relationships presented in Fig. 13. The different lines in the figure represent the four series studied herein. The starting point of each line, marked by an arrow, represents the control mixture followed by the other mixtures at increasing levels of fines.

Series I and II, which contained relatively coarse fines and for which slump was controlled by using admixture, exhibited some reduction in carbonation depth and no significant effect on shrinkage as strength increased with increasing the fines content. When slump was adjusted by additional paste, a monotonic decrease in carbonation depth was seen with the addition of fines from 40 to 120 kg/m^3 (67 to 202 lb/yd^3), along with a slight increase in strength. Further increase of fines content led to a significant decrease in carbonation depth with no further increase in the compressive strength, that is, improved durability at the same strength and *w/c*. Unlike the improved resistance to carbonation, drying shrinkage increased significantly with the increase in fines content above 40 kg/m^3 (67 lb/yd^3), with only small changes in the compressive strength.

The most important data is seen for Series III at a fines contents of 40 and 80 kg/m^3 (67 and 135 lb/yd^3). The strength of these mixtures was quite similar (both were stronger than the control mixture), but both carbonation and shrinkage increased significantly, that is, significantly reduced durability at higher strength and a constant *w/c*. It is difficult, therefore, to predict the life expectancy of these concretes based on strength or *w/c* only and performance criteria should be established as well.

SUMMARY AND CONCLUSIONS

The effect of fines content on the properties of normal-strength concrete, with a *w/c* of 0.62 and 28-day compressive strength of ~35 MPa (5076 psi), was studied. The effect of fines obtained from the crushing of dolomite stone was evaluated and compared with fines obtained from limestone, which was also much finer.

1. Increasing amounts of HRWRA are required to maintain constant workability. As the fines become smaller, admixture demands increase significantly. Very high admixture contents had negative effects on concrete properties associated with large volumes of entrained air and affecting strength development. Better compatibility of the admixture to the type of fines and separating the retarding capability from water-reducing capability is essential for better control of the properties of such concretes;

2. Adding fines to the mixture improved concrete strength. An improvement of approximately 30% was observed in the 28-day compressive strength when the coarser fines were used. Most of the improvement occurred with a relatively small addition of fines, and strength did not change much at higher fines contents. The strength at later age did not change, whereas the control mixture continued to increase in strength. Dispersion of fines by HRWRA had a better effect on strength improvement than that obtained by the addition of water; and

3. Minor increases in volume changes of fresh and hardened mixtures were observed with the coarser fines. When smaller fines were used, the sensitivity to plastic shrinkage cracking in the fresh concrete and shrinkage in the hardened concrete increased significantly. A certain decrease in carbonation rate was observed when moderate amounts of coarser fines were added. When the smaller fines were used, carbonation rate increased significantly. It should be noted that increased volume changes and carbonation rate were observed in mixtures with relatively small additions of the finer fines, despite exhibiting some improvement in compressive strength.

It appears that large amounts of fines can be used in the production of concrete with no detrimental effect on its properties, both in the fresh and hardened states, as long as its workability can be controlled using an appropriate admixture. Ultra-fine material, smaller than ~5 μm, however, may lead to a significant reduction in concrete properties, mainly due to a significant increase in the admixture demand.

In view of the results of this study, it seems that the current limitation on fines content in aggregates should be reevaluated. Larger amounts of fines can be incorporated into concrete, either as part of the aggregate itself or as an additive. Other limitations, however, should be imposed on the fraction of smaller fines, that is, approximately 5 μm or smaller. Further investigation is needed to establish this limit.

The assessment of the long-term performance of a concrete mixture is performed quite often according to its compressive strength. It is generally assumed that higher compressive strength is associated with better long-term performances. The results of this study, however, show that even while keeping the *w/c* constant, and despite higher compressive strengths obtained, there may be cases in which other properties that are related to long-term properties are adversely affected.

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