Center for By-Products Utilization

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Report No. CBU-2007-06
REP-627
January 2008

For Presentation and Publication at the Fifth International ACI/CANMET Conference on High-Performance Concrete Structures and Materials, Manaus, BRAZIL, June 18 - 20, 2008.

Department of Civil Engineering and Mechanics
College of Engineering and Applied Science
UNIVERSITY OF WISCONSIN – MILWAUKEE

EFFECT OF SHRINKAGE-REDUCING ADMIXTURE AND DIFFERENT TYPES OF AGGREGATES ON SHRINKAGE AND CHLORIDE-ION PENETRABILITY OF CONCRETE

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Synopsis: This paper summarizes recent research completed by the UWM Center for By-Products Utilization on the effects of shrinkage reducing admixture (SRA) and different types of coarse aggregate in concrete on the autogenous shrinkage and drying shrinkage properties of concrete. One source of SRA and three types of coarse aggregate [crushed quartzite stone (Qtz), semi-crushed river gravel (Gvl), and crushed dolomitic limestone (DLms)] were used in the concrete mixtures. Concrete mixtures were made with and without SRA.

The shrinkage-reducing admixture was most effective in reducing the drying shrinkage of concrete during early periods of drying. By using SRA-1, the drying shrinkage reduced by 41 to 85% at the air-storage period of seven days, and by 32 to 38% at 28 days. Concrete mixtures made with Aggregates Gvl and DLms showed a lower autogenous shrinkage than the concrete made with Aggregate Qtz. Use of Aggregate DLms appears to be useful in reducing early-age drying shrinkage of concrete, compared with use of Aggregates Gvl and Qtz. At later ages, drying shrinkage of concrete became similar regardless of the type of aggregate (Qtz, Gvl, DLms), though concrete made with Gvl showed a little higher drying shrinkage compared with concrete mixtures made with DLms and Qtz. As a whole, the effect of the type of coarse aggregate on drying shrinkage appears to be noticeable but small. Use of Aggregate Qtz led to the lowest chloride-ion penetrability (the highest resistance of concrete), followed by Aggregate Gvl, and Aggregate DLms (the highest chloride-ion penetrability).

Keywords: aggregates, air entrainment, autogenous shrinkage, chloride-ion penetration, concrete, drying shrinkage, shrinkage reducing admixture.

Yoon-moon Chun is a Research Associate at the UWM Center for By-Products Utilization (UWM-CBU) at the University of Wisconsin - Milwaukee. His research interests include the use of coal fly ash, coal bottom ash, and used foundry sand in concrete and masonry units, the use of fibrous residuals from pulp and paper mills in concrete, autogenous shrinkage of concrete, and self-consolidating concrete.

Rudolph N. Kraus is Researcher and Assistant Director of the UWM-CBU. He has been involved with numerous projects on the use of by-product materials including utilization of foundry sand and fly ash in CLSM, evaluation and development of CLSM, evaluation of lightweight aggregates, and use of by-product materials in the production of cast-concrete products.

Tarun R. Naik, FACI, is a Research Professor and Academic Program Director of the UWM-CBU. He is a member of ACI Committees 123, Research; 229, Controlled Low-Strength Materials (CLSM); and 232, Fly Ash and Natural Pozzolans in Concrete. He is Chairman of ACI Committee 555, Concrete with Recycled Materials. He is also a member of ACI Board Advisory Committee on Sustainable Development. He was Chairman of the ASCE Technical Committee on Emerging Materials (1995-2000).

INTRODUCTION

Shrinkage cracking is a major cause of concern for concrete structures. In addition to weakening the structure, shrinkage cracks have the potential to allow infiltration of moisture and chloride ions that accelerate the corrosion of steel reinforcement and reduce the durability of concrete [1, 2]. The four main types of shrinkage associated with concrete are plastic shrinkage, autogenous shrinkage, carbonation shrinkage, and drying shrinkage.

Plastic shrinkage is associated with moisture loss from freshly placed concrete into the surrounding environment. Autogenous shrinkage is the early shrinkage of concrete caused by chemical consumption of water from capillary pores due to the hydration of cementitious materials, without loss of water into the surrounding environment. This type of shrinkage tends to increase for concrete mixtures having a lower water-cementitious materials ratio (w/cm). Carbonation shrinkage is caused by the chemical reactions of various cement hydration products with carbon dioxide present in the air. This type of shrinkage is usually limited to the surface of the concrete. Drying shrinkage can be defined as the volumetric change due to the drying of the hardening concrete. This type of shrinkage is caused by the movement of water from hardened concrete into the surrounding environment [3].

Modulus of elasticity is the most important property of aggregate that directly influences drying shrinkage of concrete. Troxell et al. [4] reported that the drying shrinkage cracking of concrete increased 2.5 times when an aggregate with high elastic modulus was substituted by an aggregate with low elastic modulus. Also, a larger size of coarse aggregate permits the use of a leaner concrete mixture, resulting in lower shrinkage. Increase in the aggregates content also reduces the shrinkage of concrete [5]. The pore structure of aggregate particles may have a strong effect on autogenous shrinkage. Aggregate particles may contain water in pores, which provides the "internal curing" for hydrating cement paste, hence reducing autogenous shrinkage. Lura et al. [6] reported that the addition of lightweight aggregates (LWA) in the concrete mixture reduces the self-desiccation of cement paste. In their study LWA concrete with aggregate having a degree of saturation 50 % and 100 % exhibited autogenous swelling, up to an age of three months. On the other hand, a normal weight aggregate concrete mixture exhibited shrinkage of up to 470 microstrain (μm/m) at the same age. LWA concrete showed lower drying shrinkage at the initial age, but at later ages the rate of shrinkage was higher compared with normal-weight aggregate concrete due to lower modulus of elasticity of LWA offering less resistance to the shrinkage of the cement paste. Matsushita and Tsuruta [7] reported effects of the type of coarse aggregate on autogenous shrinkage of concrete. The coarse aggregate studied included Andesite, Crystalline Schist, and Amphibolite. They concluded that if the volume of coarse aggregate was maintained constant, the type of coarse aggregate negligibly affected the autogenous shrinkage of high-strength concrete.

RESEARCH SIGNIFICANCE

This research was conducted to evaluate the effects of a shrinkage-reducing admixture (SRA-1) and three different types of aggregates on autogenous shrinkage, drying shrinkage, and chloride-ion penetrability of concrete made with Class C fly ash. In addition, the effects of the SRA-1 on the air content, slump, and initial setting time of concrete were investigated. More test data on other concrete mixtures containing SRA-1 and SRA from two other sources are available elsewhere [1].

MATERIALS AND SPECIMEN PREPARATION

ASTM C 150 [8] Type I portland cement, ASTM C 618 [9] Class C fly ash, and natural sand meeting the requirements of ASTM C 33 [10] were used in this research. Three types of coarse aggregate were used: crushed quartzite stone (Qtz), semi-crushed river gravel (Gvl), and crushed dolomitic limestone (DLms). The coarse aggregates had a nominal maximum size of 19 mm and met the grading requirements for ASTM C 33 Size No. 67 (Nominal size of 19.0 to 4.75 mm). Shrinkage admixture (SRA-1, diethylene glycol monobutyl ether), mid-range water-reducing admixture (MRWRA-1), and air-entraining admixture (AEA-1) obtained from one source were used. SRA was added last into the concrete mixer after all the other ingredients were intermixed.

Test specimens of concrete were made and cured according to the ASTM C 192 [11]. The concrete mixer used was an electrical power-driven, revolving drum, tilting mixer.

The properties of freshly mixed concrete were determined, and test specimens were cast for the evaluation of time of initial setting (ASTM C 403 [12]), autogenous shrinkage, drying shrinkage (ASTM C 157 [13]), compressive strength (ASTM C 39 [14]), and chloride-ion penetrability (ASTM C 1202 [15]) of concrete.

The autogenous shrinkage was determined in accordance with a test method adapted from a procedure originally drafted by the Japan Concrete Institute [16]. In total, three autogenous length-change comparators were built. Each comparator was built using two dial indicators and an invar rectangular bar connecting the two ends.

In addition, a separate invar reference bar was prepared, and its length-change was measured using each comparator, periodically. The length-change of the reference bar was very small [± 10 microstrain (μm/m)] meaning that the comparator readings were reliable. To prepare concrete beam specimens for autogenous length-change, gage plugs (pins) and sealed plastic film molds (liners) were placed in steel beam molds. Then fresh concrete was placed and consolidated in the plastic molds, and covered with film covers and sealed with tape. The measurements for the autogenous length-change and temperature of concrete started at the time of initial setting of concrete. Additional measurements were taken once between 15 to 18 hours (approximately 0.7 days), and again at 24 hours. During the first 24 hours, the test setup was not disturbed; the dial indicators of each length-change comparator remained in contact with the gage plugs of each beam. Then hardened concrete beams were removed from molds and sealed with aluminum adhesive tape to prevent evaporation. After this, additional measurements were taken at the ages of 3, 7, 14, 28, and 56 days. Fig. 1 shows the testing of a hardened, sealed concrete beam for autogenous length-change. More details are available elsewhere [1] on the test setup and methods used in this research for determining autogenous length-change of concrete.

The specimens for time of setting and autogenous shrinkage were kept in sealed condition. Other test specimens were stored in a moist-curing room maintained at 23°C. For each concrete mixture, two specimens were used for time of setting, three for autogenous shrinkage, three for drying shrinkage, three for compressive strength at each test age, and three for chloride-ion penetrability at each test age. Each concrete mixture was made once.

RESULTS AND DISCUSSION

Mixture proportions

Table 1 shows the mixture proportions and fresh properties of concrete mixtures. Cementitious materials were composed of 70% cement and 30% Class C fly ash, by mass. For each of the three types of coarse aggregate, one concrete mixture was made without SRA-1, and another concrete mixture was made with SRA-1. The dosage rate of SRA-1 used was the average of the minimum and maximum dosage rates recommended by the SRA-1 manufacturer.

SRA-1 had a water-reducing effect and an air-entraining effect. Concrete mixtures containing SRA-1 required only minimal amounts of MRWRA-1 and AEA-1. Use of SRA-1 led to a considerable reduction of either the water-cementitious materials ratio (w/cm) (Mixtures S1-0.0-FA-Qtz vs. S1-1.6-FA-Qtz), the required amount of MRWRA-1 (Mixtures S1-0.0-FA-DLms vs. S1-1.6-FA-DLms), or both (Mixtures S1-0.0-FA-Gvl vs. S1-1.6-FA-Gvl). Use of SRA-1 in concrete mixtures also led to a great reduction in the required dosages of AEA-1 for all three types of coarse aggregates, Qtz, Gvl, and DLms.

Time of initial setting

Time of initial setting of concrete was determined. It was used for starting the measurements for autogenous shrinkage. The time of initial setting of concrete did not change considerably (Table 2) with SRA-1 use or the use of different types of aggregate (Qtz, Gvl, and DLms).

Autogenous shrinkage

Table 3 and Fig. 2 show the test results for autogenous shrinkage of concrete mixtures. Up to the age of at least 56 days, concrete continued to shrink because of autogenous shrinkage.

Use of SRA-1 was effective in reducing the autogenous shrinkage of concrete, especially when comparing Mixtures S1-0.0-FA-Qtz vs. S1-1.6-FA-Qtz, and Mixtures S1-0.0-FA-DLms vs. S1-1.6-FA-DLms.

As for the influence of the type of coarse aggregate, the concrete mixtures made with Aggregates Gvl and DLms showed a lower autogenous shrinkage than the mixtures made with Aggregate Qtz. The mixture S1-0.0-FA-Qtz, made with crushed quartzite stone and without SRA-1, showed a significantly higher autogenous shrinkage than the rest of the concrete mixtures. SRA-1 was highly effective when used with Aggregate DLms, resulting in the lowest autogenous shrinkage of the concrete S1-1.6-FA-DLms among the six concrete mixtures reported in this paper.

Drying shrinkage

Tables 4, 5 and Fig. 3 show the test results for drying shrinkage of concrete (after 28 days of moist curing).

SRA-1 was quite effective in reducing the drying shrinkage of concrete mixtures. The relative reduction in drying shrinkage was greater during early periods of drying. By using SRA-1, the drying shrinkage at the air-storage period of seven days reduced by 41 to 85%, and the drying shrinkage at the air-storage period of 28 days reduced by 32 to 38% (Table 5).

Fig. 3 shows the influence of the type of coarse aggregate on drying shrinkage. At the air-storage period of four days, the concrete mixtures made with SRA-1 combined with Aggregate DLms showed a lower drying shrinkage than the ones made with SRA-1 combined with Aggregates Qtz or Gvl. At air-storage periods of 14 days and later, the drying shrinkage of concrete mixtures became similar regardless of the type of coarse aggregate. Mixture S1-1.6-FA-Gvl showed higher drying shrinkage at later air-storage periods of 56 and 112 days, compared with Mixtures S1-1.6-FA-Qtz and S1-1.6-FA-DLms. As a whole, the effect of the type of coarse aggregate on drying shrinkage appears to be relatively small.

Compressive strength

Table 6 shows the test results for compressive strength of concrete.

The concrete mixtures containing SRA-1 generally showed higher compressive strength than their reference (no-SRA) concrete mixtures. This may be explained by the fact that the concrete mixtures made with SRA-1 usually had a lower w/cm compared with concrete mixtures made without SRA-1 (Table 1).

The concrete mixtures made with Aggregates Qtz and DLms (both crushed stone) showed generally higher compressive strength than the concrete mixtures made with Aggregate Gvl (semi-crushed river gravel). Mixture S1-0.0-FA-DLms showed relatively low compressive strength; the reason for this is not known.

Chloride-ion penetrability

Table 7 and Fig. 4 show the test results for electrical indication of chloride-ion penetrability into concrete. As the age increased, chloride-ion penetrability decreased.

Use of SRA-1 did not significantly increase or decrease the chloride-ion penetrability into the fly ash concrete.

As for the effect of the type of aggregate, Aggregate Qtz was the best at all test ages, leading to the lowest chloride-ion penetrability (the highest resistance of concrete to penetration). Aggregate Gvl was the second best, and use of Aggregate DLms resulted in the highest penetrability of chloride ions into concrete (the lowest resistance to penetration). The compressive strength of concrete mixtures containing Aggregate Gvl was generally lower than that of the concrete mixtures made with Aggregate Qtz or DLms (Table 6). So, there was no correlation between the compressive strength and the chloride-ion penetration resistance of concrete in this case.

CONCLUSIONS

Effects of a shrinkage-reducing admixture (SRA-1), and three types of coarse aggregate [crushed quartzite stone (Qtz), semi-crushed river gravel (Gvl), and crushed dolomitic limestone (DLms))] on properties of concrete were investigated.

Based on the experimental program conducted and the test results obtained, the following conclusions may be drawn:

Effect of SRA-1

SRA-1 had a water-reducing effect and an air-entraining effect. Partly due to their lower water-cementitious ratio (w/cm), the concrete mixtures containing SRA-1 showed generally higher compressive strength than their reference (no-SRA) concrete mixtures. Use of SRA-1 did not affect the time of initial setting of concrete and the chloride-ion penetrability into concrete, considerably. SRA-1 was effective in reducing autogenous shrinkage of concrete.

SRA-1 was effective in reducing the drying shrinkage of concrete, especially during early periods of drying when the rate of drying shrinkage would otherwise be the highest. By using SRA-1, the drying shrinkage at the air-storage period of seven days reduced by 41 to 85%, and the drying shrinkage at the air-storage period of 28 days reduced by 32 to 38%.

Effect of different types of aggregates

Change in the type of aggregate (Qtz, Gvl, and DLms) did not affect the time of initial setting of concrete considerably. The concrete mixtures made with

Aggregates Gvl and DLms showed a lower autogenous shrinkage than the mixtures made with Aggregate Qtz. The concrete mixtures made with Aggregates Qtz and DLms (both crushed stone) showed generally higher compressive strength than the concrete mixtures made with Aggregate Gvl (semi-crushed river gravel).

The concrete mixtures made with Aggregates Gvl and DLms showed a lower autogenous shrinkage than the mixtures made with Aggregate Qtz. SRA-1 was highly effective when used with Aggregate DLms, resulting in the lowest autogenous shrinkage of the concrete S1-1.6-FA-DLms among the six concrete mixtures reported in this paper.

It appears that the use of Aggregate DLms helps to reduce the early-period drying shrinkage, compared with use of Aggregates Gvl and DLms. As a whole, the effect of the type of coarse aggregate on drying shrinkage appears to be relatively small.

Use of Aggregate Qtz led to the lowest chloride-ion penetrability (the highest resistance of concrete to penetration). Use of Aggregate Gvl led to the second lowest chloride-ion penetration, and use of Aggregate DLms resulted in the highest penetrability of chloride ions into concrete (the lowest resistance of concrete to penetration).

ACKNOWLEDGEMENTS

The authors express their deep gratitude to the Wisconsin Department of Transportation (WisDOT) and the Federal Highway Administration (FHWA) for providing funding thorough the Wisconsin Highway Research Program. We are grateful to James Perry, Edward Fitzgerald, Gerald Anderson, and Stanley Woods of the WisDOT for their useful, timely, and constructive comments throughout the planning and execution of this research project.

Special thanks are expressed to Chintan Sutaria, a former Research Assistant, for his contributions to the literature review and his dedicated effort in conducting many of the concrete mixtures and testing in this research. Thanks are also due to Andrew Brauer, David Krueger, Kristina Kroening, and Nicholas Krahn for their contributions in producing concrete mixtures, testing of specimens, and data collection. Thanks to Alan Nichols for machining the invar bars and assembling the autogenous length-change comparators.

The UWM Center for By-Products Utilization was established in 1988 with a generous grant from the Dairyland Power Cooperative, La Crosse, WI; Madison Gas and Electric Company, Madison, WI; National Minerals Corporation, St. Paul, MN; Northern States Power Company, Eau Claire, WI; We Energies, Milwaukee, WI; Wisconsin Power and Light Company, Madison, WI; and, Wisconsin Public Service Corporation, Green Bay, WI. Their financial support and additional grant and support from Manitowoc Public Utilities, Manitowoc, WI, are gratefully acknowledged.

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Table 1 – Mixture proportions and fresh properties of concrete.

Mixture designation*	S1-0.0-FA-Qtz	S1-1.6-FA-Qtz	S1-0.0-FA-Gvl	S1-1.6-FA-Gvl	S1-0.0-FA-DLms	S1-1.6-FA-DLms
Cement (kg/m^3)	234	233	229	234	234	234
Class C fly ash (kg/m^3)	101	100	99	101	101	101
Water (kg/m^3)	134	125	131	121	134	131
Fine aggregate, SSD (kg/m^3)	832	829	725	740	832	833
Coarse aggregate, 19-mm max., SSD (kg/m^3)	1010	1000	1090	1110	1010	1020
Shrinkage-reducing admixture 1 (L/m^3)	0	5.26	0	5.29	0	5.27
Mid-range water-reducing admixture 1 (L/m^3)	0.85	0.84	0.49	0.20	0.92	0.23
Air-entraining admixture 1 (L/m^3)	0.15	0.02	0.16	0.02	0.31	0.02
Water-cementitious materials ratio, w/cm	0.40	0.37	0.40	0.36	0.40	0.39
Slump (mm)	50	50	75	90	60	65
Air content (%)	6.0	6.4	6.0	6.4	7.5	6.8
Air temperature (°C)	20.6	20.6	21.1	20.3	20.0	20.0
Concrete temperature (°C)	21.1	21.1	20.6	21.4	18.9	20.0
Density (kg/m^3)	2310	2300	2270	2310	2320	2320

* The number following S1- indicates the approximate dosage rate of SRA-1 in L/100 kg of cementitious materials.

Table 2 – Time of initial setting of concrete.

Mixture designation	S1-0.0-FA-Qtz	S1-1.6-FA-Qtz	S1-0.0-FA-Gvl	S1-1.6-FA-Gvl	S1-0.0-FA-DLms	S1-1.6-FA-DLms
Time of initial setting (hours)	9	10.5	8.75	7.75	10	8.75

Table 3 – Autogenous shrinkage of concrete.

Age (days)	Autogenous shrinkage* (µm/m)†					
	S1-0.0-FA-Qtz	S1-1.6-FA-Qtz	S1-0.0-FA-Gvl	S1-1.6-FA-Gvl	S1-0.0-FA-DLms	S1-1.6-FA-DLms
Time of initial setting‡	0	0	0	0	0	0
0.7	3	-6	-22	0	-24	-7
1	26	0	-10	4	-9	1
3	102	35	5	23	-5	-5
7	134	44	52	55	26	8
14	173	56	76	70	65	37
28	260	114	123	91	117	63
56	365	204	164	149	182	91

* -: Expansion. +: Shrinkage.
† 100 µm/m = 0.01 %.
‡ Refer to Table 2.

Table 4 – Drying shrinkage of concrete after 28 days of moist curing.

Air-storage period after 28 days of moist curing (days)	Drying shrinkage* (µm/m)†					
	S1-0.0-FA-Qtz	S1-1.6-FA-Qtz	S1-0.0-FA-Gvl	S1-1.6-FA-Gvl	S1-0.0-FA-DLms	S1-1.6-FA-DLms
0	0	0	0	0	0	0
4	237	113	NAv	85	160	23
7	307	153	263	155	273	40
14	407	206	380	205	390	167
28	470	290	443	300	443	293
56	520	336	503	405	483	357
112	520	373	547	450	517	380

* -: Expansion. +: Shrinkage.
† 100 µm/m = 0.01 %.
NAv = Not Available.

Table 5 – Relative reduction in drying shrinkage of concrete.

Air-storage period after 28 days of moist curing (days)	Reduction in drying shrinkage relative to no-SRA mixture (%)					
	S1-0.0-FA-Qtz	S1-1.6-FA-Qtz	S1-0.0-FA-Gvl	S1-1.6-FA-Gvl	S1-0.0-FA-DLms	S1-1.6-FA-DLms
4	0	52	0	NAv	0	85
7	0	50	0	41	0	85
14	0	49	0	46	0	57
28	0	38	0	32	0	34
56	0	35	0	20	0	26
112	0	28	0	18	0	26

NAv = Not Available.

Table 6 – Compressive strength of concrete.

Age (days)	Compressive strength (MPa)					
	S1-0.0-FA-Qtz	S1-1.6-FA-Qtz	S1-0.0-FA-Gvl	S1-1.6-FA-Gvl	S1-0.0-FA-DLms	S1-1.6-FA-DLms
1	9.0	7.9	5.7	7.2	5.6	7.5
3	22.2	25.8	18.8	22.0	19.6	24.6
7	31.1	34.2	25.7	30.2	28.5	34.4
14	36.0	40.1	30.8	35.2	35.8	42.4
28	39.4	46.6	33.3	39.5	37.9	48.3
91	49.1	55.1	42.3	46.8	41.5	57.0
182	50.9	56.7	44.3	49.0	42.3	60.3

Table 7 – Chloride-ion penetrability into concrete.

Age (days)	Chloride-ion penetrability (Coulomb)					
	S1-0.0-FA-Qtz	S1-1.6-FA-Qtz	S1-0.0-FA-Gvl	S1-1.6-FA-Gvl	S1-0.0-FA-DLms	S1-1.6-FA-DLms
28	1970	1940	2810	2390	3410	3940
56	1020	1220	1600	1540	1570	1750
182	480	550	720	720	800	850

Specimen thickness: 50 mm.
Specimen diameter: 100 mm.

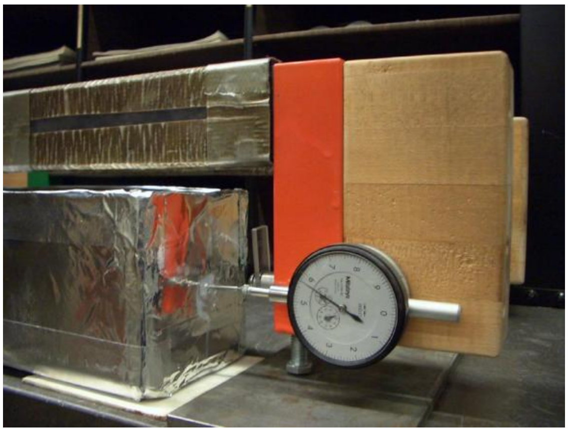

Fig. 1 – Testing of a hardened, sealed beam for autogenous length-change

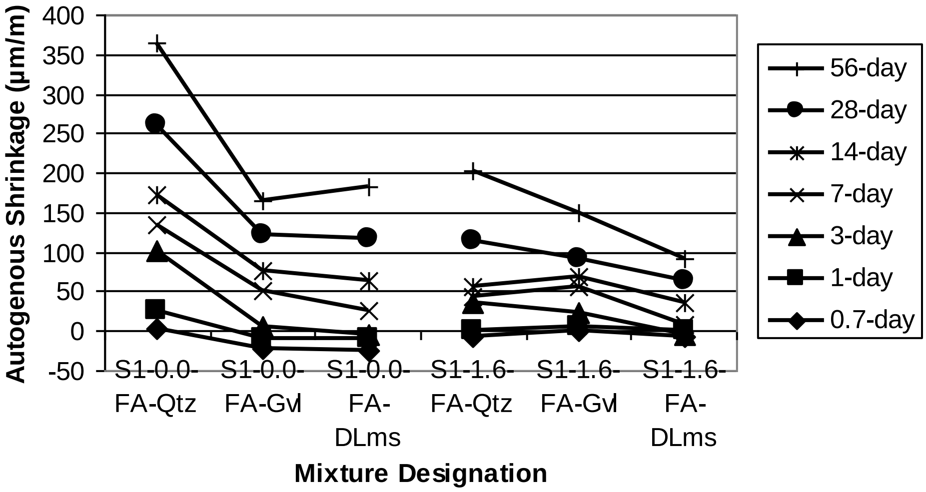

Fig. 2 – Autogenous shrinkage of concrete vs. aggregate type (Aggregates Qtz, Gvl, DLms).

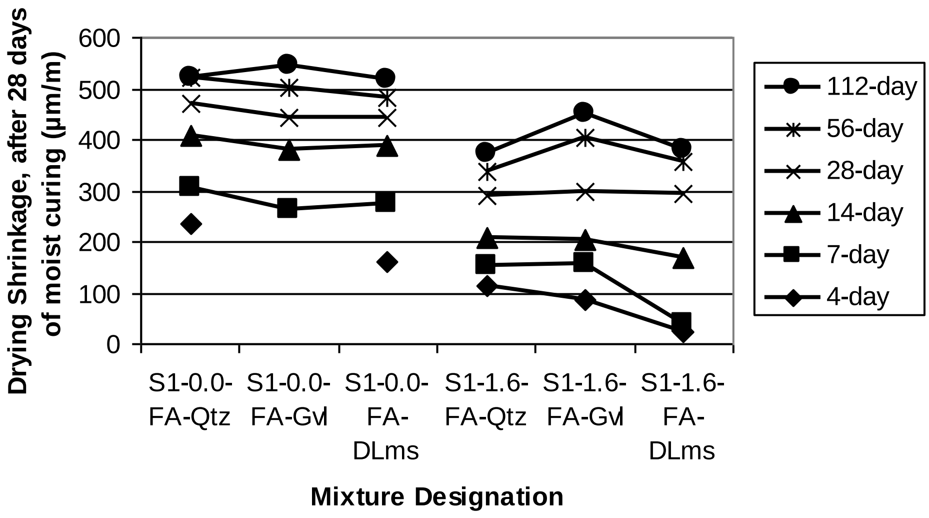

Fig. 3 – Drying shrinkage of concrete vs. aggregate type (Aggregates Qtz, Gvl, DLms).

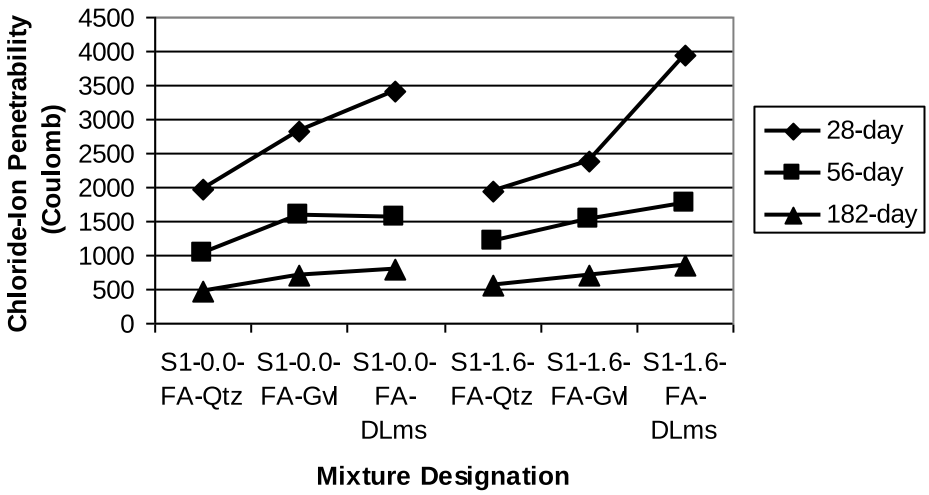

Fig. 4 – Chloride-ion penetrability into concrete vs. aggregate type (Aggregates Qtz, Gvl, DLms).