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ABSTRACT

The scope of this research was to determine the usefulness of limestone-quarry by-product material in the development of economical self-compacting concrete (SCC). Class C fly ash was also used and it was received from a power plant in Wisconsin. The main objective of this project was to evaluate the possibility for using these materials to reduce costs of expensive chemical admixtures needed for the manufacturing of self-compacting concrete. Use of quarry fines and Class C fly ash in self-compacting concrete is expected to provide significant economic benefits to quarries, coal-fired power plants, and concrete producers. Based on the extensive laboratory work, it was concluded that the limestone-quarry fines and Class C fly ash have high potential for utilization in the manufacturing of self-compacting concrete (SCC). The test data collected indicate that these materials can be used in the manufacturing of economical SCC in several different ways. When quarry fine material was used for the substitute of natural sand, it reduced the requirement of chemical admixtures, high-range water-reducing admixture (HRWRA) and viscosity-modifying admixture (VMA), without affecting the strength of SCC. The 28-day compressive strength of the mixtures made with sand replaced with quarry fines was in the range of 7,500 psi and 9,000 psi, qualifying the mixtures to be classified as high-strength SCC (≥ 6500 psi). Also by using Class C fly ash for the replacement of up to 55% of total cement by mass, high-strength SCC with the 28-day strength in

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the range of 9,000 psi and 10,000 psi was produced in an economical way. In conclusion, the use of quarry fines and Class C fly ash significantly reduced the amount of expensive chemical admixtures such as HRWRA and VMA in producing SCC.

Keywords: Admixture, Bleeding, Compressive strength, Fly Ash, Limestone Quarry, Self-compacting concrete

INTRODUCTION

Self-compacting concrete (SCC), a recent innovation in concrete technology, has numerous advantages over conventional concrete. Self-compacting concrete, as the name indicates, is a type of concrete that does not require external or internal compaction, because it becomes leveled and compacted under its self-weight. SCC can spread and fill every corner of the formwork, purely by means of its self-weight, thus eliminating the need of vibration or any type of compacting effort (Okamura - 1997). Self-compacting concrete, in its current reincarnation, was originally developed at the University of Tokyo, Japan, in collaboration with leading concrete contractors in the late 1980s. Since the mid-1980s, flowable, self-leveling, self-compacting slurry has been gaining increasing acceptance (Naik, Ramme, and Kolbeck - 1990). However, such flowable slurry typically has compressive strength of 1,200 psi or less at the age of 28 days. Prior to such flowable cement-based materials, in 1970s and 1980s, flowable, cohesive, structural-grade concrete with low water to cementitious materials ratio, with or without HRWRA, were also being used.

The notion behind developing SCC was the concerns regarding the homogeneity and compaction of conventional cast-in-place concrete within intricate (i.e., heavily-reinforced) structures and to improve the overall strength, durability, and quality of concrete (Campion, and Jost - 2000). The SCC concrete is highly flowable and cohesive enough to be handled without segregation. It is also referred to as self-consolidating concrete, self-leveling concrete, super-workable concrete, highly flowable concrete, non-vibrating concrete, and other similar names (Kurita, and Nomura, - 1998).

Hoshimoto et al. (Hashimoto, Maruyama, and Shimizu - 1989) visualized and explained the blocking mechanism of a heavily-reinforced section during the pouring of concrete and reported that the blockage of the flow of concrete at a narrow cross-section occurs due to the contact between coarse aggregates in concrete. When concrete flows between reinforcing bars, the relative locations of coarse aggregates are changed. This develops shear stress in the paste between the coarse aggregates, in addition to compressive stress. For concrete to flow through such obstacles smoothly, the shear stress should be small enough to allow the relative displacement of the aggregate. To prevent the blockage of the flow of concrete due to the contact between coarse aggregates, a moderate viscosity of the paste is necessary. The shear force required for relative displacement largely depends on the water-cementitious materials ratio (*w/cm*) of the paste. An increase of the *w/cm* increases the flowability of the cement paste; however, it may also decrease the viscosity and deformability, the primary requirements for the SCC. The SCC is flowable as well as deformable without segregation (Okamura - 1997; Campion, and Jost, - 2000; Kurita, and Nomura - 1998). Therefore, in order to maintain deformability along with flowability in paste, a superplasticizer is necessary in such concretes. With a superplasticizer, the paste can be made more flowable with little concomitant decrease in viscosity (Okamura - 1997). An optimum combination of *w/cm* and superplasticizer for achievement of self-compatibility can be derived for fixed aggregate content concrete.

Mehta (Mehta - 1986) and Neville (Neville - 1995) have suggested a simple approach of increasing the sand content, while reducing the amount of coarse aggregate by 4% to 5%, in order to avoid segregation. High-flowability requirement of SCC allows the use of higher amounts of mineral admixtures in its manufacturing. Use of mineral admixtures such as fly ash, blast furnace slag, limestone powder, and other similar materials increase the fine materials content of the concrete mixture (Okamura - 1997). The use of mineral admixtures also reduces the cost of concrete. The incorporation of one or more mineral admixtures, or powder materials having different morphology and grain-size distribution, can improve particle-packing density and reduce inter-particle friction and viscosity. Hence, it improves deformability, self-compatibility, and stability of the SCC (Sonebi, Bartos, Zhu, Gibbs, and Tamimi - 2000).

By using fly ash and blast furnace slag, Yahia et al. (Yahia, Tanimura, Shimabukuro, and Shimoyama - 1999), and Naik and Kumar (Naik, and Kumar - 2003) reported a reduction in the dosages of viscosity-modifying agent and superplasticizer in SCC needed to obtain similar slump-flow compared to concrete made with portland cement only. The well-known beneficial advantages of using fly ash in concrete, such as improved rheological properties and reduced cracking of concrete due to the reduced heat of hydration of the concrete, also allows its use in SCC by using the fly ash as filler.

A highly flowable concrete is not necessarily self-compacting because SCC should not only flow under its own weight but also fill the entire form and achieve uniform compaction without segregation. Fibers are sometimes used in SCC to enhance its tensile strength and to delay the onset of tension cracks due to heat of hydration resulting from high cement content in SCC (Kurita, and Nomura, 1998). Use of fly ash in SCC is also reported (Naik, and Kumar - 2003; Bouzoubaâ, and Lachemi 2001) for the development of economical and environmental friendly SCC.

The scope of this research reported in this paper was to determine the usefulness of limestone-quarry by-product material in the development of economical self-compacting concrete (SCC). Class C fly ash was also used and it was received from a power plant in Wisconsin. The main objective of this project was to evaluate the possibility for using these materials to reduce costs of expensive chemical admixtures needed for the manufacturing of self-compacting concrete.

MATERIALS

A test program was designed to measure chemical and physical properties of cement, sand, gravel, limestone-quarry fines, and Class C fly ash materials. These properties were necessary before determining possible uses of these materials in developing economical SCC. Properties of HRWRA and VMA were obtained from the manufacturer. Chemical analysis of cement, fly ash, and limestone-quarry fines are given in Table 1. Physical properties of aggregates and Class C fly ash as shown in Table 2 and 3.

Particle Size Distribution

Particle size distribution of the crushed stone, gravel, sand, quarry fines, and fly ash used in this research are presented together in Fig. 2 for comparison.

The limestone-quarry by-product used in this research was “crushed limestone screenings” received from a limestone company in Wisconsin.

The material was white to light gray in color. The as-received moisture content of the quarry fines was not very high, at around 3% of oven-dry material (105°C) by mass.

A proprietary copolymer HRWRA that complies with the requirements of ASTM Standard Specification for Chemical Admixtures for Concrete (C 494) for Type F, High Range Water Reducing Admixture (HRWRA), and Viscosity-Modifying Admixture (VMA) were used as a HRWRA and VMA in this research.

MIXTURE PROPORTIONS, RESULTS, AND DISCUSSIONS

Self-compacting concrete typically has a higher content of fine particles and different flow properties than the conventional concrete. It has to have three essential properties when it is ready for placement: filling ability, resistance to segregation, and passing ability. However, the components of SCC are similar to other plasticized concrete. Self-compactability of concrete can be affected by the physical characteristics of materials, mixture proportioning, and moisture content of its ingredients. The mixture proportioning is based upon creating a high-degree of flowability, while maintaining a low (< 0.40) *w/cm*. Development of SCC mixtures typically requires a series of trial mixtures using the available sources of concrete-making materials.

In order to develop SCC mixtures efficiently, for the results reported herein, only the compressive strength of SCC was determined initial stage of the laboratory investigation. A series of concrete mixtures were produced using different by-product materials, and the compressive strength of concrete was determined by testing three 4" × 8" cylinders per each test age for each mixture.

Development of SCC Reference Mixture Using Class C Fly Ash

In order to develop a SCC mixture that would be the basis for mixtures that will use quarry fines, a series of mixtures used Class C fly ash to replace a part of cement in Control SCC mixture (i.e., mixture without any fly ash). The cement was replaced with fly ash at a fly ash-cement replaced ratio of 1.25 by mass. SCC mixtures were made by replacing 20%, 35%, 45%, and 55% of cement with fly ash. The mixture proportions and other details of the SCC mixtures containing fly ash, as well as those of Mixture 15R (Control) are given in Table 4. Compressive strength results for Mixtures 15R (Control) to 21 are presented in Table 5.

Overall, as the replacement level of cement with fly ash increased from 0% to 20%, 35%, 45%, and 55%, the 3-day compressive strength of SCC decreased. The decrease in strength was probably due to longer initial-setting time and final-setting time of SCC containing a considerable amount of fly ash (Naik, 1997). However, with the increase in age, concrete with a replacement of cement with fly ash gained considerable strength. The strength of Mixture 17, made with 20% replacement of cement with fly ash, was equivalent or higher to that of Mixture 15R at 3 and 7 days, and considerably higher strength than that of Mixture 15R (Control) at 28 days. SCC mixtures made with 35% replacement of cement with Class C fly ash (Mixtures 16 and 18) showed slightly less 7-day strength and higher 28-day strength compared with Mixture 15R (Control).

SCC mixtures made with 45% (Mixtures 19 and 21) and 55% (Mixture 20) replacements of cement with fly ash showed very low 3-day strength, and the mixture made with 55% replacement of cement showed low 7-day strength. However, the 28-day strength of the SCC mixtures with 45% fly ash was equivalent to that of Control Mixture 15R. Mixture 20 with 55% fly ash showed a considerable strength gain after the age of 7 days, and its 28-day strength was nearly equivalent to that of Control Mixture 15R.

Based upon the fresh SCC test results and compressive strength, Mixture 18 was selected as the reference mixture for quarry fines.

Use of Quarry Fines for Partial Replacement of Sand

For evaluating the effect of quarry fines in SCC, Mixture 18 (35% replacement of cement with fly ash) was selected as the reference for this series of mixtures. Limestone-quarry fines were used to replace 10%, 20%, 30%, 40%, and 50% of the sand used in Mixture 18 on a replacement ratio of 1:1 by mass. The mixture proportions and other details of the mixtures incorporating quarry fines as a replacement of sand, as well as those of the "new" Reference Mixture 18, are given in Table 6.

Regardless of the replacement level of sand with quarry fines, the requirement of VMA remained approximately the same as the Reference Mixture 18, probably because the quarry fine is angular and finer material replacing rounded and coarser natural sand. However, the requirement of HRWRA decreased gradually as the replacement level of sand with quarry fines increased.

Compressive strength results for Mixtures 15R (Control), 18 (Reference), and 22 through 27 are presented in Table 7. When sand was replaced with quarry fines, compressive strength generally increased (sometimes decreased to some extent). Overall, the 3-day and 7-day strengths were higher, and the 28-day strength was lower compared with Reference Mixture 18. The 28-day strength of concrete made with partial replacement of cement with Class C fly ash combined with partial replacement sand with quarry fines, was equivalent to that of the Control Mixture 15R made without Class C fly ash or quarry fines. Since sand occupies considerable volume in SCC concrete mixtures, replacement of sand with quarry fines can be considered an economical high-volume use option for quarry fines, which are generally not used but discarded as “useless” material.

ECONOMIC BENEFITS ANALYSIS

Use of Class C fly ash and quarry fines in self-compacting concrete is expected to provide economic benefits to coal-powered power plants, quarries, and concrete producers in Wisconsin.

Material Cost and Compressive Strength of Concrete Mixtures

Mixture proportions influenced the material cost and compressive strength of the self-compacting concrete (SCC) mixtures reported in this research. Changes in material cost and strength of SCC are compared in the following sections.

Partial Replacement of Sand with Quarry Fines

As shown in Fig. 3, replacement of up to 50% of natural sand with quarry fines lowered the material cost of self-compacting concrete slightly and did not affect the strength of the concrete significantly. About 70% of the savings in the material cost were due to the reduced dosage of HRWRA, and most of the remaining savings were directly due to partial replacement of sand with quarry fines. All of the concrete mixtures showed relatively high 3-day compressive strength, ranging from 3,655 psi to 5,080 psi. The 28-day compressive strength of the concrete mixtures was in the range of 7,630 and 9,150 psi, qualifying the concrete mixtures to be classified as high-strength concrete.

Partial Replacement of Cement with Class C Fly Ash

Partial replacement of portland cement with Class C fly ash lowered the material cost and the early-age strength of self-compacting concrete, (Fig. 4), and increased the long-term strength of concrete (Fig. 4).

About 60% of the savings in the cost of materials for the SCC with fly ash were due to the reduction in the required quantity of HRWRA for producing self-compacting concrete mixtures, which is due to the partial replacement of cement with fly ash. Almost 30% of the savings were because of the partial replacement of cement with fly ash, and the rest of the savings were due to the reduced dosage of VMA.

The 3-day compressive strength of the concrete made with 35% replacement of cement with Class C fly ash (Mixture 18 [Ref.]) was 4140 psi, which was actually quite high at that early age. Mixtures 18 (Ref.), 19, and 20 made with 35%, 45%, and 55% replacement of cement with fly ash showed the 28-day compressive strength of 9,055, 8,650, and 6,930 psi, respectively. Thus they can be classified as high-strength concrete (≥ 6,500 psi). Moreover, although the durability of concrete was not determined in this research, it is well known that the use of fly ash improves the durability of concrete significantly.

Potential Material-Cost Savings in Wisconsin

The comparison of the material cost and compressive strength of self-compacting concrete mixtures in the previous section showed that there are at least two options of using by-products beneficially in producing self-compacting concrete:

1. Replacement of up to 50% of natural sand with quarry fines saved the material cost without affecting the early-age and late-age strength of concrete.

2. Replacement of up to 35% of cement with Class C fly ash saved the material cost and improved the long-term strength of concrete, while maintaining a relatively high level of 3-day compressive strength.

SUMMARY AND CONCLUSIONS

Based on the extensive laboratory work, it is shown that that the limestone-quarry fines and Class C fly ash have a noticeable improvement and high potential for utilization in the manufacturing of self-compacting concrete (SCC). The test data collected indicate that these materials can be used in the manufacturing of economical SCC in different ways. When the quarry fines and fly ash were used as partial replacements of sand and cement, respectively, the requirements of expensive chemicals such as HRWRA and viscosity modifying agent (VMA) decreased.

By using quarry fines for the replacement of up to 50% of sand by mass, high-strength SCC with the 28-day compressive strength in the range of 7,630 psi and 9,150 psi was produced.

By using the Class C fly ash for the replacement of up to 55% of cement by mass, high-strength SCC with the 28-day compressive strength in the range of 6,900 psi and 10,200 psi was produced.

General conclusions based on this laboratory investigation are as presented below:

1. Replacement of up to 50% of sand with the limestone-quarry fines resulted in:
   (a) Some reductions in required amount of HRWRA and little changes in U-flow test results; and
   (b) Either some increase, or at times decrease, in compressive strength.

2. Replacement of a part of cement with the Class C fly ash resulted in:
   (a) Large reductions in required amounts of chemical admixtures (HRWRA and VMA) and considerable improvement in U-flow test results at the same level of slump-flow;
   (b) Some reduction in the 3-day compressive strength and some increases in the 28-day compressive strength for 20% and 35% replacements of cement;
   (c) A large reduction in the 3-day strength and some reduction in the 28-day strength for 45% replacement of cement; and

   (d) Large reductions in the 3-day and 7-day strengths and some reduction in the 28-day strength for 55% replacements of cement.

3. In summary, based on the chemical-admixture demands and strength of self-compacting concrete, it was observed:
   (a) Partial replacement of sand with limestone-quarry fines appears to be economically beneficial, without noticeably affecting the strength of concrete;
   (b) Use of the Class C fly ash as a partial replacement of cement appears to be very beneficial to the economy and the long-term strength gain of concrete.

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Table 1 - Chemical Analysis of Materials (% by mass) (Pera - 2003)

Material	Limestone-Quarry Fines	Class C Fly Ash	Type I Portland Cement
SiO_2	n.d.	35.8	20.0
Al_2O_3	0.1	20.6	4.8
Fe_2O_3	n.d.	5.8	2.1
$SiO_2 + Al_2O_3 + Fe_2O_3$	0.1	62.2	26.8
MnO	n.d.	n.d.	0.1
MgO	20.8	5.6	2.2
CaO	32.6	24.7	66.0
Na_2O	n.d.	2.2	0.2
K_2O	n.d.	0.5	0.5
TiO_2	n.d.	1.5	0.2
P_2O_5	n.d.	1.0	n.d.
SO_3	n.d.	1.2	2.5
LOI	46.5	1.2	1.4

n.d.: Not detected.

Table 2 - Physical properties of Class C fly ash

Test Parameter	Class C Fly Ash, %	ASTM C 618 limits, %
Fineness Retained on 45 µm Sieve (%)	13	≤ 34
Specific Gravity	2.56	—
Strength Activity Index with Cement, 28-day (% of Control)	113	≥ 75

Table 3 - Physical properties of aggregates

Properties	Natural Sand	Gravel
Specific Gravity	2.68	2.71
Absorption	1.2	3.0
Maximum Nominal Size (mm)	4.75	9.5

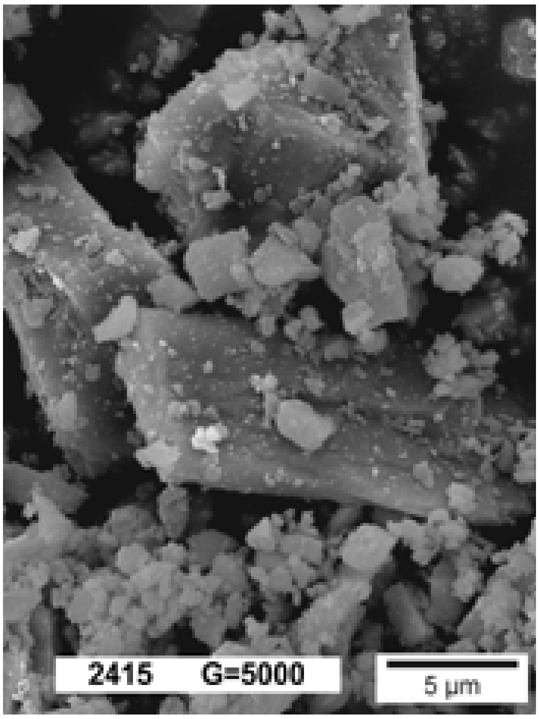

Fig. 1 - SEM of limestone-quarry fines (0).

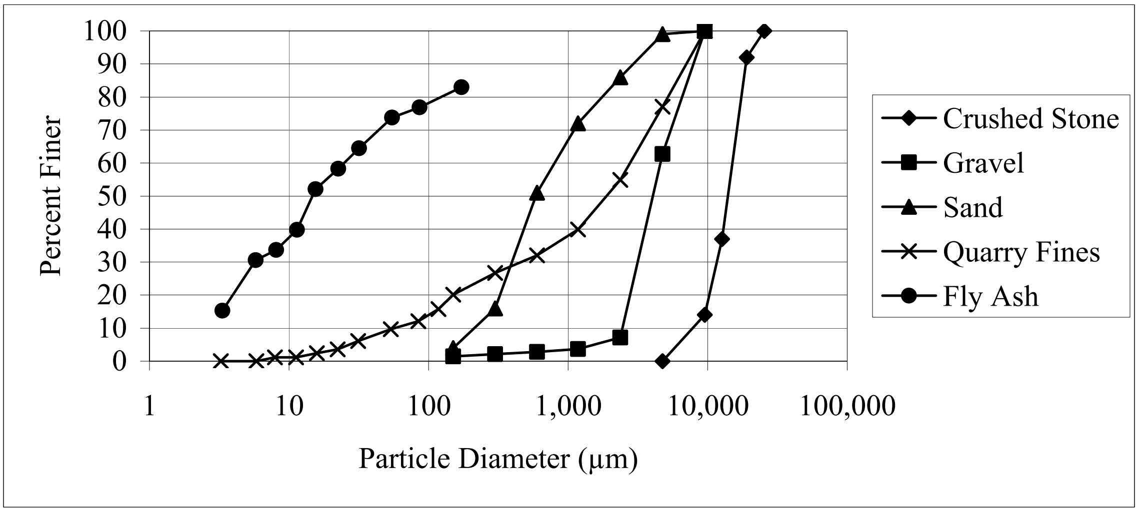

Fig. 2 - Particle size distribution of materials by sieve analysis combined with hydrometer analysis.

Table 4 - Mixture Proportions of SCC (Cement Replaced : Fly Ash = 1 : 1.25)

Mixture Number	15R (Control)	16	17	18 (Ref.)	19	20	21*
% Replacement of Cement with Fly Ash	0	35	20	35	45	55	45
Cement (lb/yd^3)	727	464	560	447	385	306	385
Fly Ash, Class C (lb/yd^3)	0	313	178	300	393	480	393
Sand (lb/yd^3)	1636	1610	1601	1556	1588	1582	1580
3/8 " Gravel (lb/yd^3)	1468	1448	1450	1424	1454	1453	1453
Water (lb/yd^3)	248	208	214	239	229	212	228
HRWRA (gal./yd^3)	1.64	4.3	2.1	0.96	0.6	0.6	0.6
VMA (gal./yd^3)	0.75	1.0	1.0	0.6	0.4	0.36	0.4
w/cm	0.34	0.29	0.30	0.35	0.33	0.31	0.33
w/cm†	0.36	0.34	0.33	0.37	0.34	0.32	0.34
Slump-Flow (in)	26.75	27.5	28	27	27	27.5	27
Segregation	Some	Some	None	NA	NA	NA	NA
Bleeding	Some	None	None	Some	Some	None	Slight
U-Flow, H1 - H2 (in.)	0.2	0.25	0.25	0.25	0.25	0.25	0.25
U-Flow, H2/H1 (%)	98	98	98	98	98	98	98
Air Content (%)	1.7	0.3	1.5	1.5	1.4	2.7	1.1
Density (lb/ft^3)	151.8	151.3	148.2	147.3	150.1	149.6	150.0

* Repeat of Mixture No. 19.
† Considering water in chemical admixtures.
NA: Not available.

Table 5 - Compressive Strength of Mixtures 15 – 21
(Cement Replaced : Fly Ash = 1 : 1.25)

Mixture No.‡	Cement Replac. (%)*	Compressive Strength (psi)								
		3-day	4-day	5-day	6-day	7-day	28-day	56-day	91-day	182-day
15R (Control)	0	6530	…	…	…	7345	8650	…	9790	…
17	20	…	6475	…	…	7725	10180	…	…	…
16	35	4855	…	…	…	6585	9250	…	…	…
18 (Ref.)	35	4140	…	…	…	6310	9055	…	…	…
19	45	205	…	…	…	4405	8650	9915	10560	11090
21†	45	…	3630	4260	4725	5100	7690	…	9785	…
20	55	130	150	215	330	1245	6930	…	…	…

‡ Arranged in ascending order of cement replacement with fly ash.
* Replacement of cement with Class C fly ash.
† Repeat of Mixture 19.

Table 6 - Mixture Proportions of SCC (Sand Replaced : Quarry Fines = 1 : 1)

Mixture Number	18 (Ref.)	22	23	24	25	27
% Replacement of Cement with Fly Ash	35	35	35	35	35	35
% Replacement of Sand with Quarry Fines	0	10	20	30	40	50
Cement (lb/yd^3)	447	450	455	460	457	459
Fly Ash, Class C (lb/yd^3)	300	301	304	307	307	306
Sand (lb/yd^3)	1556	1416	1262	1123	963	806
Quarry Fines (lb/yd^3)	0	156	319	476	641	806
3/8 " Gravel (lb/yd^3)	1424	1432	1438	1454	1445	1451
Water (lb/yd^3)	239	241	243	245	244	245
HRWRA (gal./yd^3)	0.96	0.8, 0.9‡	0.8	0.5, 0.7, 0.7‡	0.53, 0.66‡	0.53, 0.66‡
VMA (gal./yd^3)	0.6	0.4, 0.6‡	0.55	0.43, 0.43, 0.55‡	0.53, 0.53‡	0.43, 0.53‡
w/cm	0.35	0.35	0.35	0.35	0.35	0.35
w/cm†	0.37	0.36	0.36	0.36	0.36	0.36
Slump-Flow (in.)	27	26, 27‡	28, 28, 28‡	25, 28, 27‡	24, 26.5‡	24, 27.5‡
Segregation	NA	None	NA	NA	NA	NA
Bleeding	Some	None	Some	Some	None	None
U-Flow, H1 - H2 (in.)	0.25	0.25	0.25	0.25	0.375	0.375
U-Flow, H2/H1 (%)	98	98	98	98	97	97
Air Content (%)	1.5	0.9	0.7	0.5	0.9	0.5
Density (lb/ft^3)	147.3	148.0	149.5	151.0	150.6	151.2

‡ Initial, intermediate (if any), and total quantities of HRWRA and VMA, and corresponding slump-flow values.

† Considering water in chemical admixtures.

NA: Not available.

Table 7 - Compressive Strength of Mixtures 15, 15R, 18, and 22 - 27 (Sand Replaced : Quarry Fines = 1 : 1)

Mixture No.	Cement Replac. (%)[*]	Sand Replac. (%)[†]	Compressive Strength (psi)					
			3-day	7-day	28-day	56-day	91-day	182-day
15R (Control)	0	0	6530	…	8650	…	9790	…
18 (Ref.)	35	0	4140	6310	9055	…	…	…
22	35	10	4200	6365	8800	9315	10505	10945
23	35	20	4355	6290	7630	9830	9765	9745
24	35	30	4510	6665	9150	10225	11060	10600
25	35	40	3655	6500	8730	10335	11150	11215
27	35	50	5080	6875	8300	10500	9740	11375
Avg.[#]	35	30	4360	6540	8520	10040	10440	10780

[*] Replacement of cement with Class C fly ash.

[†] Replacement of sand with limestone-quarry fines.

[#] Average of results for Mixtures 22, 23, 24, 25, and 27

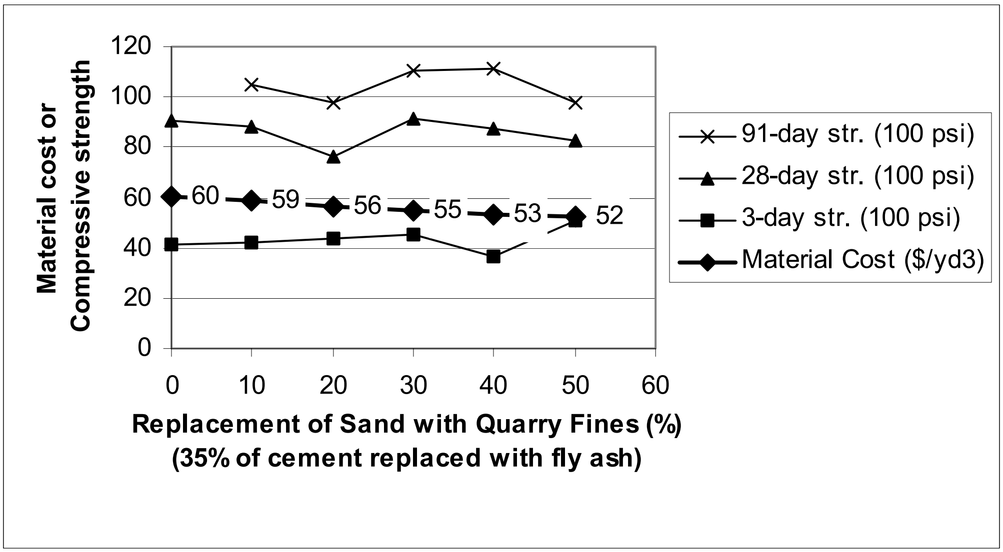

Fig. 3 - Material cost and compressive strength of SCC as influenced by partial replacement of sand with quarry fines (Mixtures 18 [Ref.], 22, 23, 24, 25, & 27).

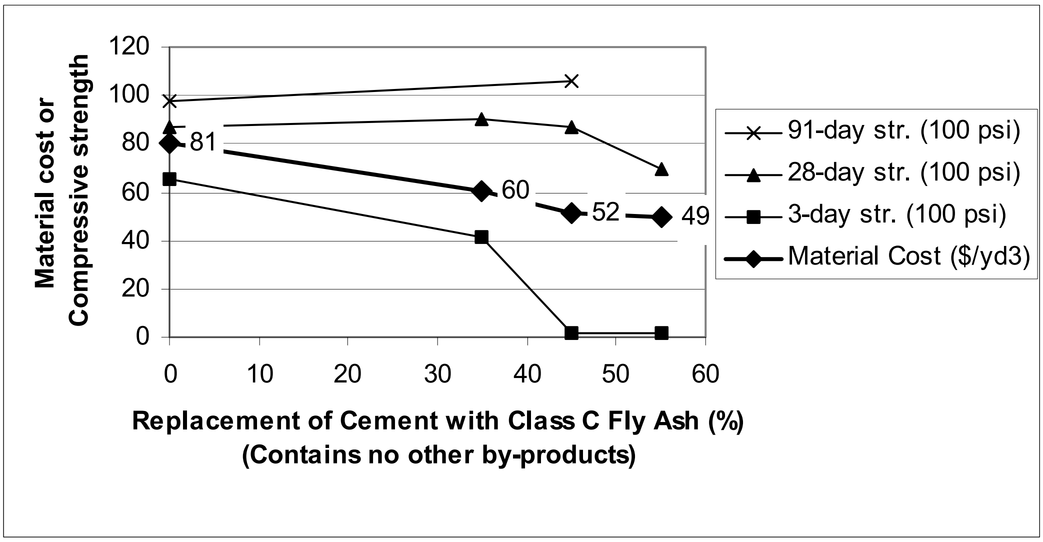

Fig. 4 - Material cost and compressive strength of SCC as influenced by partial replacement of cement with Class C fly ash (Mixtures 15R [Control], 18 [Ref.], 19, & 20).