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Production of Self-Compacting Concrete Using Jordanian Oil Shale Ash

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ABSTRACT

The potential of using Jordanian oil shale ash (OSA) as partial replacement of the cement on fresh and mechanical properties of self-compacting concrete (SCC) was investigated in depth. Six SCC mixtures were prepared with limestone filler and varying cement mass replacements of 0-30% OSA. The binder materials content was kept constant at (350 kg/m3) while the water-to-binder ratio was changed from 0.5 to 0.68 depending upon the amount of mixing water needed to achieve the required fresh properties. Standard cylinders (100x200 mm) were cast, then cured in water for 7, 28 and 56 days before being tested under compression to evaluate the mechanical properties of SCC.

The strength of the SCC concrete decreased with higher OSA replacement contents although maintaining a higher value than that of conventional concrete made at almost the same cement factor. In general, replacement contents of cement by OSA not larger than 10% imparted limited negative impact on obtained mechanical properties. The SCC mixtures studied experienced high flowability, filling ability and resistance against segregation as indicated by the several tests carried out on fresh mixtures.

KEYWORDS: Oil shale ash, Self-compacting concrete, Mechanical properties.

INTRODUCTION

In Jordan, oil shale is abundant and widely spread in seventeen regions on and under surface (Khedaywi and Al-Qadi, 2008). The economic feasibility and the environmental impacts of using oil shale as a source of energy have been studied thoroughly. One of the major withdrawals of using oil shale is the production of huge quantities of a byproduct known as oil shale ash (OSA) with high disposal cost. The environmental problems associated with the production of oil shale byproduct and the high cost of its disposal have promoted many researchers to investigate the potential of using the resulting ash in flexible pavements construction or concrete industry (Khedaywi and Al-qadi, 2008; Smadi and Haddad, 2001). The incorporation of OSA in concrete contributed to improving resistance to alkali-silica reaction and had limited negative impact on strength for replacement percentages less than 15% (Smadi and Haddad, 2003; Yougnobali et al., 1993). A most recent study by Ivanauskas et al. (2008) indicated that the replacement of cement mass by OSA changed water demand to achieve required normal consistency and even reduced the water demand when 15% replacement of cement by OSA was applied.

Self-compacting concrete (SCC) represents one of the most outstanding advances in concrete technology in recent decades as its use offers many benefits to the work environment manifested by reducing labor needed, shortening construction time, eliminating

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vibration process and noise hazards. Another advantage is the ability to be cast in heavily reinforced elements and structures with a complicated geometry (Sonebi, 2003). The basic components of SCC are practically the same as those used in conventional concrete. Economic, workable and durable SCC requires the use of relatively cheap pozzolanic materials such as OSA to replace part of the cement and/or fine fillers used in its production.

Several published works have tackled the potential of using various pozzolanic additives in the production of SCC. Kim et al. (1996) and Yahia et al. (1999) studied the properties of SCC with replacements of fly ash or blast furnace slag. They reported that the replacement of cement by 30% fly ash resulted in improving workability and flowability and those additives contributed to reducing the amount of superplasticizer needed to obtain similar slump flow as that of SCC with pure Portland cement. These findings agreed with the study by Bouzoubaâ and Lachemi (2001) which revealed that an economical SCC may be successfully developed by incorporating high volumes of class F fly ash.

Table 1. Chemical composition of the cement used

Compound	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO
Percentage	62.9	28.2	5.05	4.2	2.8
Compound	SO_3	$(K_2O)eq$	LOI	IR	
Percentage	3.1	0.80	1.40	1.10	

Table 2. Physical properties of the cement used

Property	Value
Specific gravity	3.15
Blain fineness (m^2/kg)	418.8-502
Average particle size (µm)	13
Color	Gray

Table 3. Physical properties of the limestone aggregates

Physical Properties	Coarse (limestone)	Fine (limestone)
B.S.G.(dry)	2.53	2.25
F.M.	N.A.	2.7
Absorption (%)	1.34	2.67
U.W.(loose)	1421	N.A.

B.S.G.: Bulk Specific Gravity (dry basis); F.M.: Fine Modulus; U.W.: Unit Weight (kg/m^3); N.A.: Not applicable.

Bigonzzi and Sandrolini (2005) investigated the production of SCC using tire rubber. The results indicated that concrete compressive strength and stiffness decreased with increasing the amount of rubber in these SCC mixtures, although maintaining relatively higher values than those of ordinary Portland cement concrete mixtures with similar amount of tire rubber wastes. In another study, Ghezal and Khayat (2002) found that the replacement of a large volume of cement by 100 kg/m^3 of limestone powder (LSP) has shown to reduce the cement content needed to achieve a given slump flow, viscosity and compressive strength at early ages. Such concrete can exhibit a greater resistance to surface settlement compared with similar concrete with low dosage of LSP.

The need for fine fillers in SCC whether used as a replacement of cements or fine particles promoted researchers to try fillers from various sources. Being pozzolanic in its nature, finely graded OSA is expected to work as an effective filler in the production of SCC. Yet, the ash contribution to mechanical and fresh properties of SCC needs to be established.

Experimental Program

Six different SCC mixtures were prepared with Portland cement type I of 52.5 MPa strength grade at different water to cement ratios and weight replacements of cement by OSA ranging from 10-30% before beig tested using various workability test setups. Fifty four standard SCC cylinders (150 x 300 mm) were cast from these mixtures to evaluate the mechanical properties for hardened SCC at wet curing ages of 7, 28 and 56 days.

Table 4. Chemical analysis of OSA

Component	Percentage by Weight
SiO_2	19.43
AL_2O_3	6.75
Fe_2O_3	1.89
CaO	46.22
MgO	0.96
SO_3	7.6
K_2O	0.50
TiO_2	0.24
LOI	5.50
Blaine Fineness	$550 m^2/kg$

Table 5. Sieve analysis of OSA

Size (μm)	20	45	63	90	150
Retained (%)	55-60	18-22	9-12	2.5-4.5	0-0.9

Materials Properties

This section presents the properties of materials used including cement, fine and coarse aggregates, limestone filler, OSA and high range water reducers and retarders.

Cement: Ordinary Portland cement was used in preparing different SCC mixtures. The chemical composition and the physical properties of the cement used are presented in Tables 1 and 2, respectively.

Aggregates: Limestone from El-Hallabat region in the northeastern part of Jordan was used in the preparation of the SCC mixtures. The coarse aggregate particles had a maximum size of 19 mm, whereas the fine aggregate particles had a fineness modulus of approximately 2.7. The gradation of the aggregates was modified to meet the ASTM limits, as observed in Fig. 1. All typical physical tests were performed on the aggregate coarse and fine particles. Results are summarized in Table 3.

Filler: Limestone powder passing sieve # 100 was used to maintain SCC cohesiveness and prevent aggregate segregation. The absorption values and the unit weight of the filler used were 13.8% and 1920 kg/m^3, respectively.

Oil Shale Ash (OSA): The oil shale was obtained from crushing, burning to a temperature of 650^{o}C then grinding oil shale rock chunks that were obtained from the southern part of Jordan. The OSA particles, which have Blaine fineness and specific gravity of 550 m^2/kg and 2.74, respectively, were angular with rough and porous surfaces, as shown in the scanning electronic microscope picture of Fig.2. The chemical composition of the OSA was obtained and is listed in Table 4. The particle size distribution performed on the grinded OSA indicated that more than 80% of the particles passed sieve number 45 µm, as indicated in Table 5.

Table 6. Mix proportions for different SCC mixtures used in the study

Mix	Cement (kg/m^3)	OSA (kg/m^3)	OSA %	Limestone (kg/m^3)		C.A. (kg/m^3)	Water (kg/m^3)	S.P. (%)	w/b
				Filler	Fine				
Control	350	0	0	125	590	710	175	1.5	0.50
SCC1	315	35	10	125	590	710	187	1.7	0.53
SCC2	297.5	52.5	15	125	590	710	198	1.8	0.57
SCC3	280	70	20	125	590	710	210	2.0	0.60
SCC4	262.5	87.5	25	125	590	710	225	2.2	0.64
SCC5	245	105	30	125	590	710	232	2.3	0.66

FA: Fine aggregates, CA: Coarse aggregates, S.P.: Super Plasticizer, w/b: water binder ratio.

Table 7. Initial setting time for OSA cement pastes

OSA (%)	Water/binder [a]	Setting time (minutes)
0	0.50	90
10	0.53	111
15	0.57	117
20	0.60	120
25	0.64	128
30	0.66	140

a: water/binder ratio corresponding to normal consistency.

Admixtures: A Structro W450 high range water reducer, supplied by FOSROC Company, Jordan, was used in all mixtures at varying contents (1.5-2.3%) by cement weight. The specific gravity of the superplasticizer was 1.11. A retarder and water reducing admixture under the commercial name "Conplast RP200", that was supplied by the same company, was also used in the SCC mixtures to further enhance flowability and delay setting time.

Mix Proportions

SCC mixtures were designed according to the rational mix design method recommended by Okamura and Ozawa (1995). The principle of the mix design method is that coarse and fine aggregate content is fixed so that self-compactability of the fresh concrete is achieved by adjusting only the water/bind ratio and superplasticizer content. Many trial mixes were prepared to obtain the best proportion depending on the properties of the materials used. The total content of binding material was kept constant for all mixtures at (350 kg/m^3) while the mass ratio of sand to coarse aggregate was kept constant at 1.

Six SCC mixtures were prepared including one control (without OSA replacement). The five mixtures had 10, 15, 20, 25 and 30% OSA replacement of cement. The contents of water, high range superplasticizers and the retarding admixture were adjusted in each mix to achieve workability requirements for SCC. A summary of the mix proportions used are listed in Table 6.

Table 8. Fresh property tests carried on various SCC mixtures

Mix	Slump flow (mm)	T_{500mm} (sec)	T_f (seconds)	T_{5min} (seconds)
Control	680	4.5	10	12.0
SCC1	692	3.0	11	12.0
SCC2	672	3.5	10	11.5
SCC3	710	2.5	9.0	10.0
SCC4	660	4.5	7.0	9.0
SCC5	670	5.0	7.0	9.0

T_{500mm}: time taken for concrete to reach the 500 mm spread circle;
T_f: V-funnel flow time after keeping the concrete in the funnel for 10 sec;
T_{5min}: V-funnel flow time after keeping the concrete in the funnel for 5 min.

Table 9. Mechanical properties of SCC mixtures prepared at varying OSA replacements

% of OSA	Compressive stress (MPa)			Toughness		
	7 days	28 days	56 days	7 days	28 days	56 days
0	33.5	39.3	44.3	297	207	119
10	26.3	31.5	35.6	187	202	156
15	21.5	25.7	28.5	128	129	204
20	20.0	24.3	26.7	298	160	196
25	18.2	22.7	24.7	314	169	178
30	16.2	20.2	22.1	296	187	219

Mixing, Casting and Curing

The mixing process was performed in accordance with the ASTM-C192 using a tilting drum mixer of 0.15 m³ volume capacity. Initially, little amount of water was poured in the mixer to wet its inside surface, then the entire quantity of coarse aggregate was placed in the mixture and its surface was wetted with water under continuous mixing. Specified amounts of cement and OSA were then added to coat the aggregate surfaces, followed by an alternative addition of fine aggregates, cement, limestone powder and water. The last one-third of water quantity was added with the superplasticizers and the retarder admixtures. The fresh properties of SCC were evaluated using slump flow diameter, T_{500} and V-funnel tests. For further investigation on the properties of the hardened mixtures, nine cylindrical specimens (150 x 300 mm) were cast without compaction. The surface of each specimen was smoothly finished by a trowel. All the specimens were demolded after 24 hours and placed in a curing tank for periods of 7, 28 and 56 days.

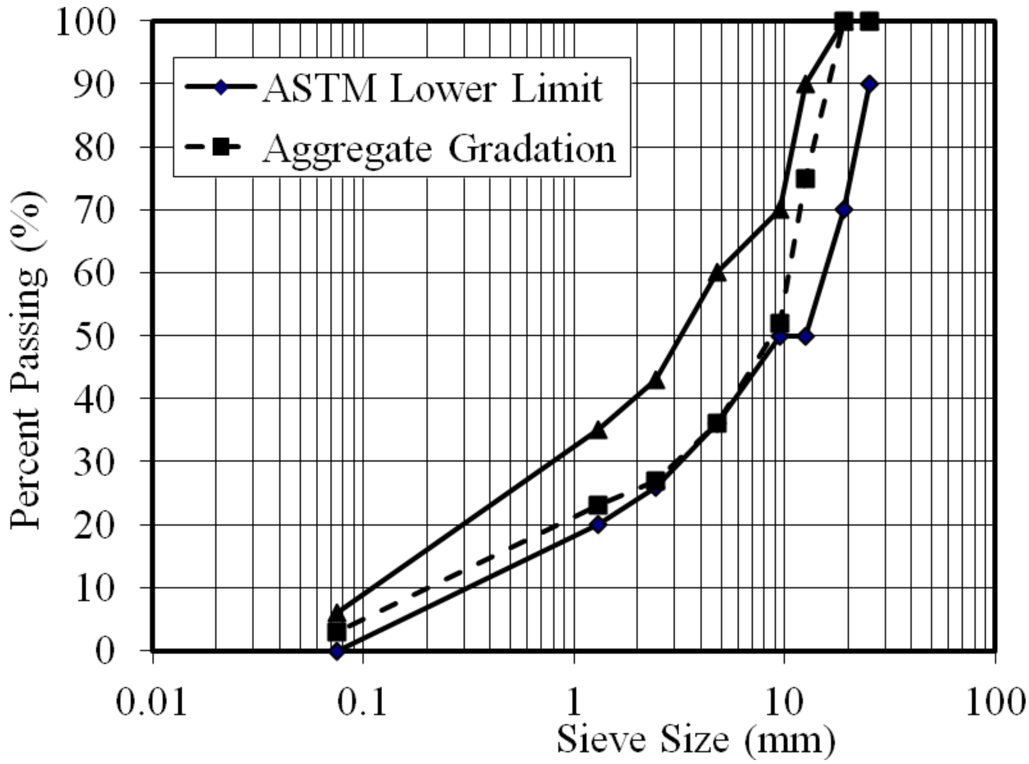

Figure 1: Combined gradation for coarse and fine limestone aggregates

Workability Test

Four different workability tests were carried out on various SCC mixtures; namely slump flow, T_{500}, V-funnel and V-funnel at $T_{5minutes}$ tests. Descriptions of these tests are presented in subsections to follow.

Slump Flow Test

The slump flow test is a measure of the flowability of concrete and is carried out in accordance to the ASTM C 143. The dimensions of the frustum cone used in this test are the same as those for slump cone test (200 and100 mm bottom and top diameters, respectively and 300 mm height). The diameter of the concrete after full flow was taken as slump flow value as shown in Fig. 3. For an SCC, the slump flow should range from 650 to 800 mm, EFNARC (2002).

T_{500} Test

The T_{500} test is used for evaluating the segregation resistance of SCC. T_{500} is the time required for the concrete to reach the 500 mm spread circle after raising the slump cone vertically and allowing the concrete to flow out freely. According to EFNARC (2002), SCC should have a T_{500} value between 2 and 5 seconds.

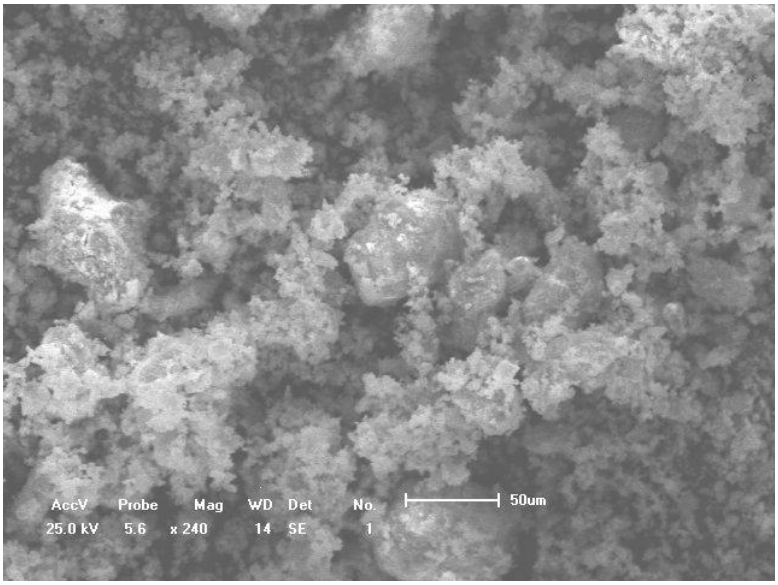

Figure 2: SEM picture of the used OSA

Figure 3: Measurement of slump flow

V-Funnel Test

V-funnel test is a measure of the filling ability of SCC. A schematic of the V-funnel used is shown in Fig. 4. The V-funnel is first filled with fresh concrete before the trap door is opened after 10 seconds to allow SCC to flow out under its own gravity and the time required to a full discharge of concrete from the funnel is recorded as "flow time". A flow time between 8 and 12 seconds is recommended for SCC according to EFNARC (2002).

V-funnel at $T_{5minutes}$

This test gives an indication of SCC resistance to segregation. The test was conducted immediately after the V-funnel test without cleaning or moistening the inside surfaces of the V-funnel apparatus. The funnel was refilled with concrete without compacting or tapping before the trap door was opened after 5 minutes of filling the funnel. The time for complete discharge was recorded as the flow time at $T_{5minutes}$. According to EFNARC (2002), the additional increase in the discharge time due to the 5-minute waiting should be in the range of 0 to 3 seconds.

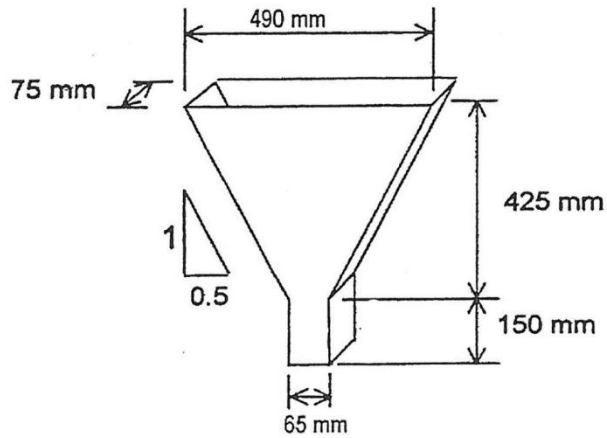

Figure 4: A schematic of the V-funnel apparatus used in testing

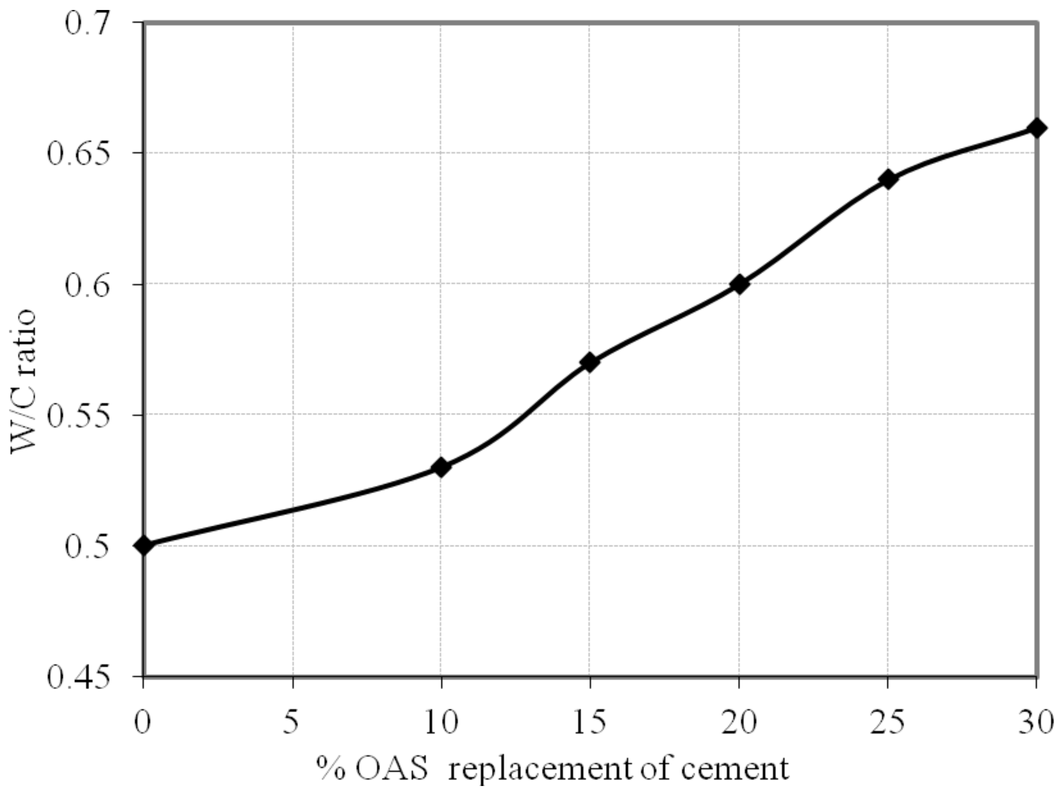

Figure 5: Water-to-cement ratio at normal consistency *versus* percentage replacement by OSA

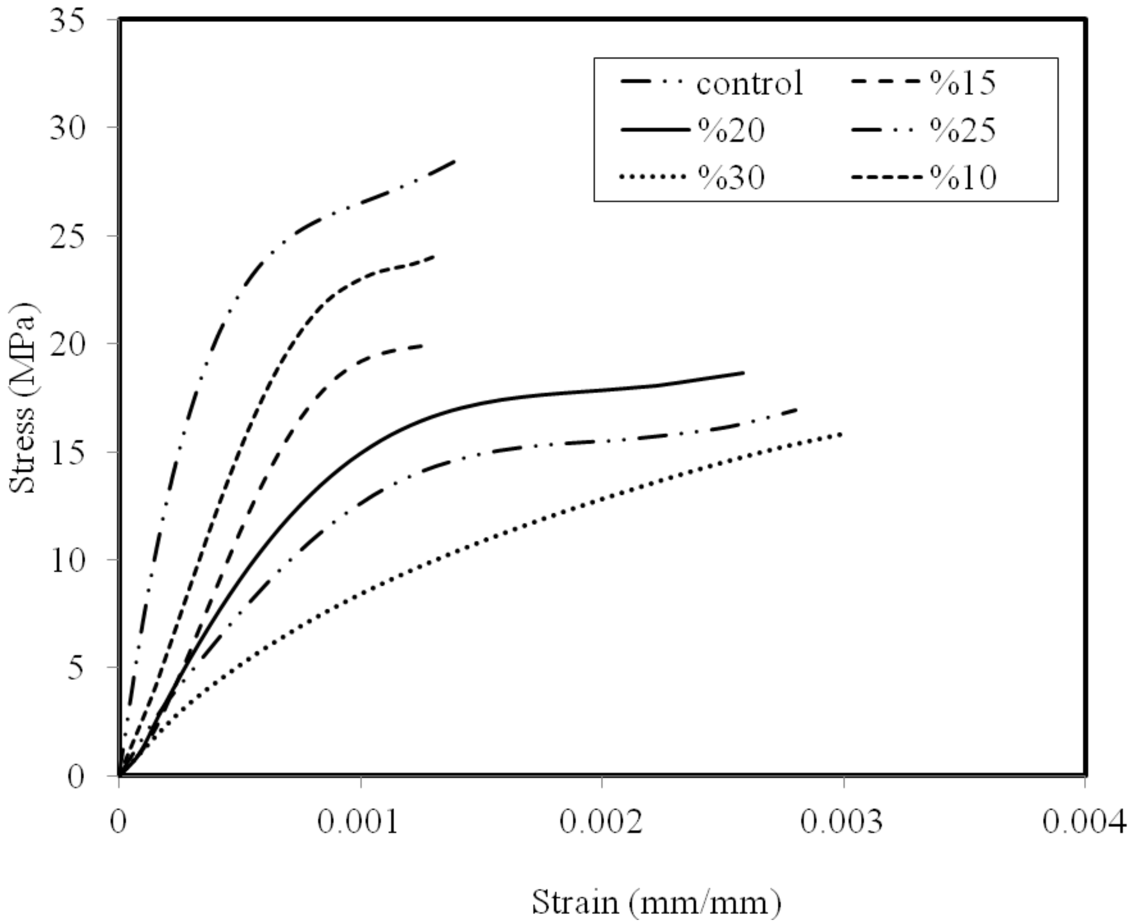

Figure 6: Stress-strain curves for SCC prepared at different OSA replacements and tested after 7 days

RESULTS AND DISCUSSION

Properties of Fresh Paste

In order to understand the behavior of SCC mixtures incorporating OSA as a partial replacement of cement, two standard ASTM tests were carried out on the cementitious blend; namely normal consistency and setting time according to ASTM C191 and C953. Fig. 6 depicts the w/c ratio corresponding to normal consistency *versus* percentage replacement by OSA. It is clear that the water demand increased significantly with OSA replacement percentage. This is referred to the relatively higher specific surface of the OSA as compared to that of the cement it replaced. The extra amounts of water, needed for mixtures with 5, 10, 20, 25 and 30% OSA, were 6, 14, 20, 28 and 32% of that used in the mixture without OSA, respectively.

Table 7 shows that the setting time was increased with increasing the cement replacement by OSA. The percentage increase in the setting time for pastes at replacements at 5, 10, 20, 25 and 30% was 23.3, 30, 33.3, 42.2 and 55.5 %, respectively. The setting times for all pastes confirm with ASTM and Euro code limits set at a minimum of 60 and 45 minutes, (ASTM, 2000 and EN, 2005).

Properties of SCC

The results of slump flow, T_{500}, V funnel and V-funnel at 5 minutes tests conducted on fresh SCC are all listed in Table 8. The slump flow of the mixture was in the range of 660 to 710 mm; indicating a relatively high deformability of SCC. The mixtures viscosity was determined by measuring the time T_{500} required to reach a 500 mm spread diameter in the slump flow test. For all the mixes, T_{500} was $\leq$ 5 seconds; satisfying the upper limit set at 5 seconds according to EFNARC (2002).

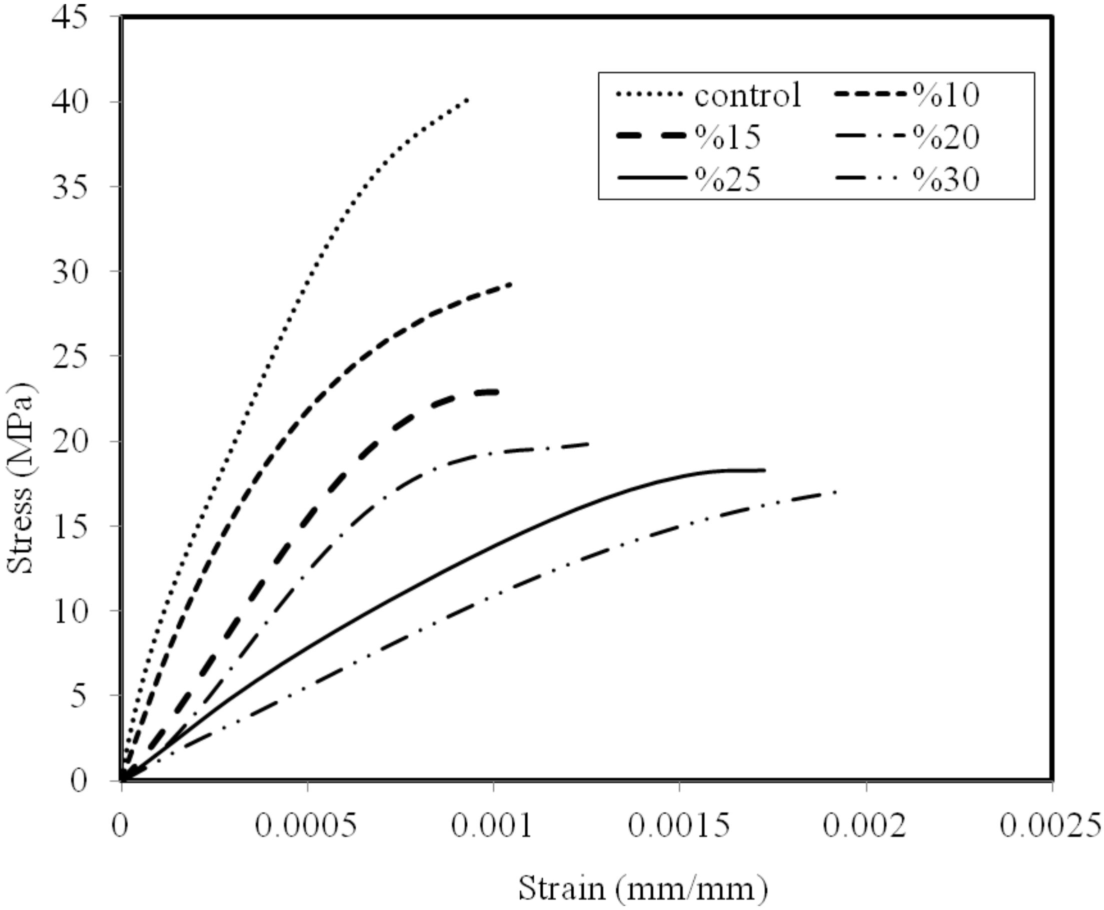

Figure 7: Stress-strain curves for SCC prepared at different OSA replacements and tested after 28 days

The flow time obtained from V_{funnel} test decreased with higher percentage replacement of cement by OSA, with flow time ranging from 7 to 11 seconds according to EFNARC (2002). The flow time after 5 minutes showed an increase in the flow time between 1 and 2 seconds over that measured after just 10 second waiting for corresponding mixtures. This increase is within the standard limit of 0-3 seconds according to EFNARC (2002).

Properties of Hardened Concrete

Stress-Strain Diagram: The stress-strain diagrams for SCC, prepared at a constant binder content of 350 kg/m^3 with different percentages of OSA replacement by cement and cured for 7,28 and 56 days, are presented in Figs. 7 through 9, respectively. The curves showed a typical linear behavior followed by a non-linear behavior owning to softening of strained concrete. As the percent of OSA replacement increased, the curves of stress-strain diagram experienced a gradual decrease in their linearity up to 15% OSA replacement. Beyond that, they tend to be non-linear at a relatively low stress level. The decrease in linearity with increasing OSA replacement was accompanied by a decrease in ultimate compressive strength and an increase in strain peak stress. Furthermore, the curves pertaining to various curing periods indicate clearly a decrease in SCC rigidity as the replacement by OSA was increased.

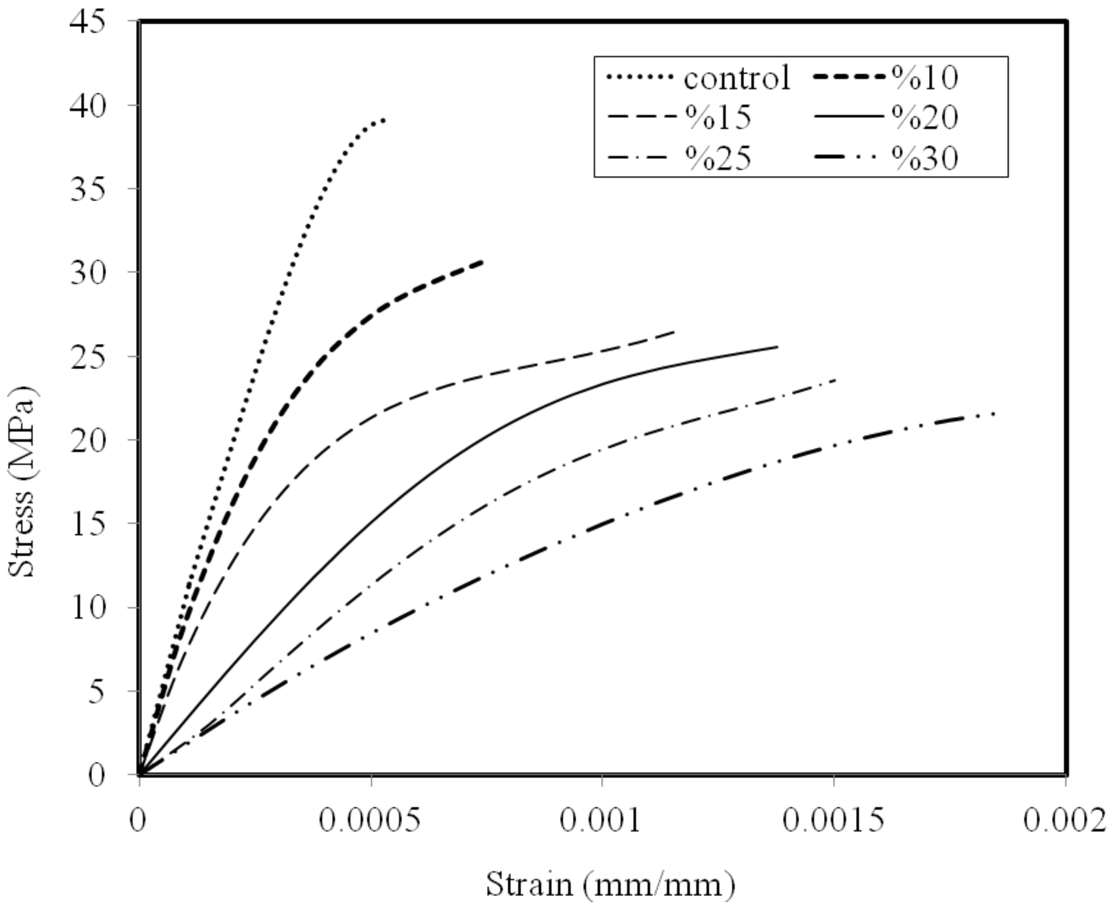

Figure 8: Stress-strain curves for SCC prepared at different OSA replacements and tested after 56 days

Mechanical Properties: The average compressive strength and toughness results of SCC mixtures, prepared at different OSA replacements of cement, are listed in Table 9. The average compressive strength of the specimens prepared at 0% OSA replacement was 33.5, 39.3 and 44.3 MPa at 7, 28 and 56 days, respectively. The strength for SCC cured from 7 to 56 day periods and prepared at 10, 15, 20, 25 and 30% replacements ranged from (16.2 to 26.3), (20.2 to 31.5) and (22.1 to 35.6) MPa, respectively. The compressive strength results graphically presented in Fig. 10 indicated the adverse effect of increasing OSA content on the compressive strength. The reduction in strength was moderate at 10% OSA replacement and became significant at 15%. At 30% OSA replacement, the percentage reduction in strength for specimens cured for 7, 28 and 56 days was 51%, 48% and 50%, respectively. The dramatic decrease in strength with OSA replacement is referred to the use of relatively higher quantities of water so as to compensate for loss in the fresh properties of SCC, because the workability enhancing additives used have reached their extreme allowable limit. The toughness showed a decrease for SCC at OSA replacements of 5-25% and an increase at 30%. The increase in toughness at 30% OSA replacement is referred to the significant increase in SCC softening behavior.

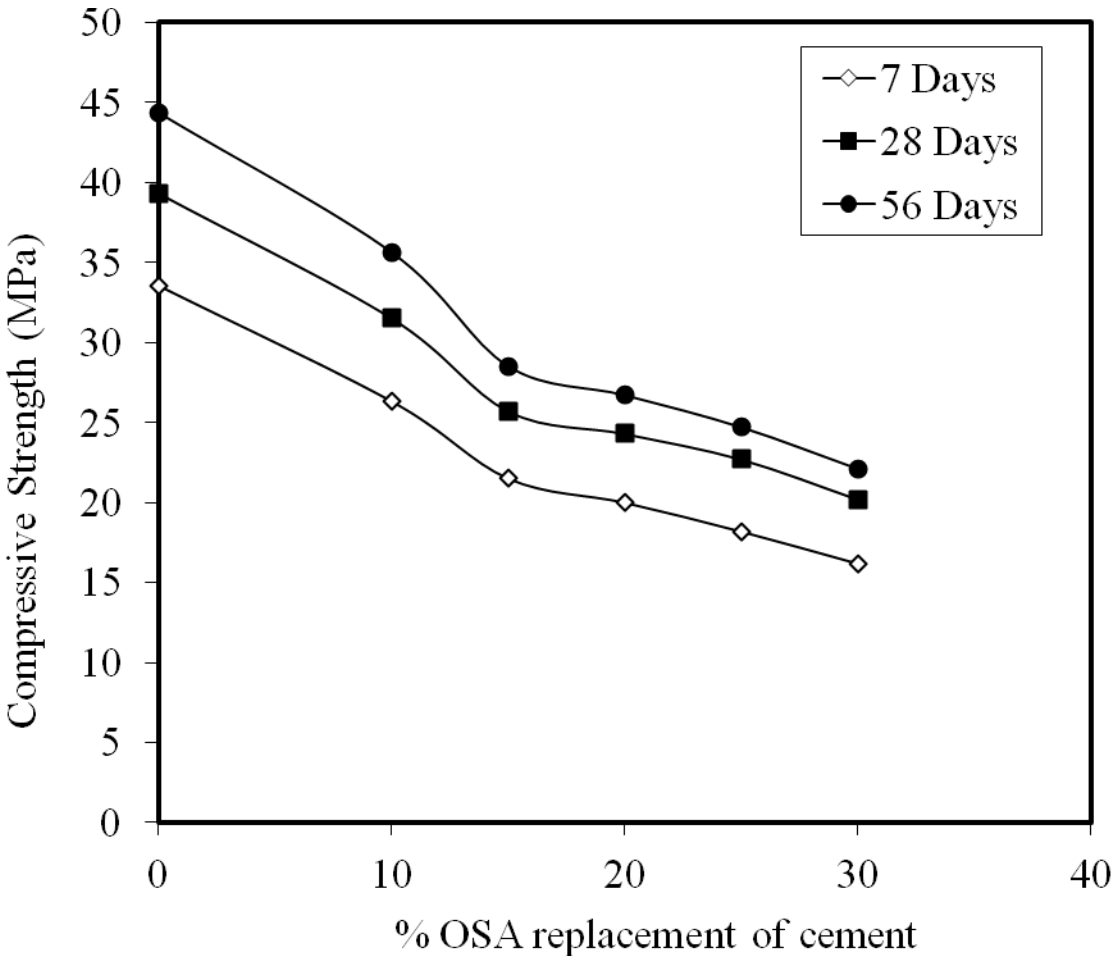

Figure 9: The effect of OSA replacement on the strength of concrete cured for 7, 28 and 56 days

SUMMARY AND CONCLUSIONS

An experimental study was undertaken to investigate the potential of using OSA in producing SCC. Six different SCC mixtures were prepared at a constant binder factor of 350 kg/m^3 with OSA replacement of cement from 0 to 30%, before being tested for fresh properties using slump flow and V-funnel flow test methods. Standard cylinder specimens (100x 200 mm) were also cast from these mixtures to evaluate the mechanical properties over the curing time.

The use of higher contents of OSA increased the demand for water and lubrication admixtures in order to maintain the fresh properties as expressed in terms of the parameters of workability tests within acceptable ranges. The obtained SCC mixtures passed requirements for flowability, filling ability and resistance against segregation. Tests carried out to investigate the effect of OSA replacement on mechanical properties revealed a negative impact of raising the replacement content of cement by OSA beyond 10%. In general, it may be stipulated that there is a potential of using OSA at limited replacement percentages of cement to produce SCC of satisfactory fresh and hardened properties. On the other hand, the use of OSA at a high replacement percentage of cement demands relatively high quantities of water and chemical admixtures to achieve the required fresh properties and yields unsatisfactory strength grades.

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