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Synopsis: The feasibility of using crushed post-consumer glass as a partial replacement of sand in concrete has been studied. To suppress the deleterious reaction between the alkali in cement and the silica in crushed post-consumer glass (ASR), a Class F fly ash was used in the experiment with the cement replacements of about 15, 30, and 45 percent by mass using a ratio of fly ash inclusion to cement replaced of about 1.25. Therefore, actual fly ash to total cementitious materials ratio was 18, 35, and 51 percent by mass. For each combination of cement and fly ash, 15%, 30%, and 45% volume of SSD sand were replaced with crushed glass. The compressive strength and splitting tensile strength of concrete were determined at specified ages for each mixture. Alkali silica reaction was evaluated according to ASTM C 1260 (Mortar Bar Method). Test results indicate that both compressive strength and splitting tensile strength of concrete decrease slightly with an increase in the replacement rate of sand with crushed glass. At lower replacement rates (less than 45%), the Class F fly ash could only delay the onset of expansion, while with high amount of fly ash concrete was immune to ASR.

Key words: alkali-silica reaction; crushed post-consumer glass; fly ash.

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INTRODUCTION

Approximately 170 thousand tons of post-consumer glass is thrown away each year in the state of Wisconsin, USA, population of about 5 million. Due to the co-mingling of colors, only a small fraction of glass can be economically recycled in the bottling and container industry. Efforts had been made for many years to use such glass in construction. Laboratory tests conducted to determine the effects of substituting fifteen percent crushed glass for a portion of the fine aggregate in an asphalt paving mixture indicated that the mixtures containing either coarse or fine crushed glass had lower Marshall stabilities and dry tensile strengths compared to a control mixture [1]. Therefore, such application is very limited. Naik and Kraus [2] at University of Wisconsin-Milwaukee Center for By-Products Utilization have just completed a project using post-consumer glass in flowable slurry, which contained very little amount of cement. ASR in such application is not a concern. Due to the concern about alkali-silica reaction glass has not been commercially used in structural concrete although some investigations have reported positive results. Studies by Meyer et al. [3, 4] at Columbia University indicated that when waste glass was ground to finer that 300 μm, it could replace up to 10% of sand in concrete masonry blocks without the concern of alkali-silica reaction. However, this is considered a costly and a low-volume glass use solution.

Numerous experimental investigations [5-7] over the last 30 years have shown that addition of fly ash is an effective method to mitigate the detrimental effects of ASR. Using Pyrex post-consumer glass as reactive aggregate, Dunstan [5] evaluated the effectiveness of 17 fly ashes on ASR. He concluded that a low calcium oxide content ash generally produces smaller expansion compared with high calcium oxide content ash. However, it was also reported that the available alkali content of ash, instead of calcium oxide content, is the key factor in controlling ASR. When the available alkali content of the ash is greater than 1.5%, there is a pessium limit [6]. In a study of the performance of twelve fly ashes in the accelerated mortar bar test (ASTM C 1260), Thomas [7] found that the expansion at 14 days linearly increases with the ratio of (Na_2Oequ + $CaO)/SiO_2$.

In the study reported here, a single source of fly ash with known history of suppressing ASR expansion was selected. The objective was using this fly ash to mitigate the detrimental expansion due to the reaction between alkali from cement and silica from the post-consumer glass.

RESEARCH SIGNIFICANCE

There is a great potential of using the post-consumer, co-mingled colors, broken glass in structural concrete if the alkali-silica reaction can be suppressed by judiciously selecting fly ash and effective mixture proportion. This study attempts to provide information about the interaction between the cement replacement with fly ash and the sand replacement with crushed glass. There is a lack of published data on this issue.

EXPERIMENTAL PROGRAM

Materials

A Type I cement from the Lafarge Company was used in this experiment. Its chemical composition and physical properties are listed in Table 1. A Class F fly ash from New Mexico was selected due to its known history of reducing ASR expansion (Table 2). Crushed lime stone with the maximum size of 19 mm (0.75 in) and natural sand with a fineness modulus of 2.8 were obtained from a local supplier. Both materials satisfied the specification of ASTM C 33 and are non-reactive regarding the alkali-silica reaction. The crushed glass was obtained from a local glass-recycling center. Its gradation did not satisfy ASTM C 33. However, the combinations of the natural sand and the crushed glass investigated fell between the limits specified in ASTM C 33 (Fig. 1).

Mixture Proportion

Four series of concrete mixtures were proportioned to have a slump between 5 cm and 10 cm (2 to 4 inches) and to have an average compressive strength of 35 Mpa (5,000 psi) at 28 days. Mixtures of Series A did not contain fly ash. In mixtures of Series B, C, and D, 15, 30, and 45% (by mass) of cement was replaced with Class F fly ash, respectively. To achieve equivalent compressive strength at 28 days, one part of cement was replaced by 1.25 part of fly ash by mass. The fine aggregate in each series was partially replaced with the crushed glass. The replacements were 0, 15%, 30%, and 45% by volume of SSD sand. Therefore, totally 16 concrete mixtures were investigated. The detailed mixture proportions are shown in Table 3.

Scope of Tests

For each mixture listed in Table 3, the properties of fresh concrete were evaluated and 100 mm by 200 mm (4" by 8") cylinders were cast for compressive strength and splitting tensile strength determination at ages of 3 days, 7 days, 28 days, 91, and 182 days. Cylinders were cured in standard moisture room. 25 x 25 x 285-mm (1" x 1" x 11-1/4") mortar bars were prepared from the mortar part sieved from the concrete mixture. After 24 hours curing in moisture room, mortar bars were stripped from molds and cured in 80 °C hot water for another 24 hours. Then the initial length was recorded for each bar. The mortar bars were immersed in 1.0 N (40 g sodium hydroxide per 1000 ml solution) alkali solution at 80 °C up to six weeks as required by ASTM C 1260. The length of each bar was determined after immersion for every two days in the first two weeks and every week thereafter.

TEST RESULTS AND DISCUSSIONS

Properties of Fresh Concrete

The properties of fresh concrete are shown in Table 3. The water reducing effect of this fly ash was not significant. Crushed glass has two opposite effects on the water requirement of the concrete mixtures. Its angular shape tends to decrease the slump of concrete, while its glassy surface tends to increase it. The net effect, as shown in Table 3, was very little.

Compressive Strength and Splitting Tensile Strength of Concrete

Test results on compressive strength and splitting tensile strength of the 16 mixtures are summarized in Fig. 2 and Fig. 3, respectively. In each series, the compressive strength decreased with the increase of glass content. With the same amount of glass content, mixtures in Series B (15% cement replacement) had the highest compressive strength at all test ages. High cement replacements (30% in Series C and 45% in Series D) decreased the early strength, but the 28-day compressive strength was little influenced and the late strength (91 and 182 days) increased significantly compared with the control mixture without fly ash. For all mixtures, the splitting tensile strength was less affected by the glass content (Fig. 3). The glass particles were rougher and larger than sand particles. The rough particles tend to increase tensile strength while large particles tend to decrease it. It appears that these positive and negative effects were balanced when the glass particles were incorporated in the concrete mixture. Thus, the tensile strength was not considerably affected by the glass content. Cement replacement with Class F fly ash had the similar influence on splitting tensile strength as on compressive strength.

Expansion of Mortar Bars

The relative linear expansion of mortar bars in 1.0 N sodium hydroxide solution is shown in Figs. 4 through 7. For each mixture, the relative expansion at a particular age is an average of the measurements on four mortar bars. The mixtures without fly ash (A1 to A3) started expansion only after four days in alkali solution and the total expansion exceeded 0.1% after 14 days, even with only 15% glass (Fig. 4). As noted in the Appendix of ASTM C 1260, "expansions less than 0.10% at 16 days after casting (14 days in alkali solution) are indicative of innocuous behavior; expansions more than 0.20% at 16 days after casting are indicative of potentially deleterious expansion, and expansions between 0.10 and 0.20% at 16 days after casting include both aggregates that are known to be innocuous and deleterious in field performance". Based on these criteria, for all replacement levels, the combination of sand and glass were classified as potentially deleterious. When 15 or 30% cement was replaced by the Class F fly ash, the onset of expansion was delayed to 14 days and the expansion accelerated thereafter. When 45% cement was replaced by the Class F fly ash, the expansion was successfully suppressed (Fig. 7). For all mixtures the expansion at ages of 14 days and 28 days almost linearly increased with the glass content (Figs. 8 and 9). However, the overall expansion of mixtures with fly ash was much lower than the mixtures without fly ash at the same test ages (Figs. 10 and 11). No pessium limit was found in this experiment regarding to the amount of fly ash or the amount of active aggregate.

CONCLUSIONS

This study evaluated the feasibility of using glass from one source as a partial replacement of sand in concrete. The results of this study should be verified using several other sources of crushed glass. Based on the results obtained in this investigation, the following conclusions may be drawn.

1. Strength of concrete is slightly reduced when sand is partially replaced by crushed glass.
2. Crushed glass is highly reactive in sense of alkali silica reaction. Expansion of mortar bars without fly ash increases almost linearly with the content of crushed glass.
3. At low replacement level (less than 45%), fly ash acts only as the delayer of the onset of expansion, but the long-term expansion is still very high.
4. The deleterious expansion can be successfully suppressed by 45% or higher cement replacement with Class F fly ash, regardless of the amount of crushed glass in concrete.

ACKNOWLEDGEMENT

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Table 1 - Chemical Composition and Physical Properties of Cement

Composition and Properties	Cement, Type I	ASTM C150, Type I
Chemical Composition		
SiO_2, %	23.0	--
Al_2O_3, %	5.6	--
Fe_2O_3, %	2.9	--
MgO, %	2.2	≤ 6.0
SO_3, % When $C_3A \leq 8\%$ When $C_3A > 8\%$	3.5	≤ 3.0 ≤ 3.5
CaO	62.2	--
$Na_2O + 0.658K_2O$, %	0.3	≤ 0.60*
Loss on Ignition, %	1.1	≤ 3.0
Physical Properties		
Fineness, m^2/kg, by air permeability test method	380	≥ 280
Autoclave Expansion, %	-0.01	≤0.80
Compressive Strength, Mpa, 1 day 3 days 7 days 28 days	 10.8 21.7 29.0 39.9	 -- ≥ 12.4 ≥ 19.3 ≥ 27.6*
Time of setting, vicat method Initial set, minute Final set, minute	 165 205	 ≥ 45 ≤ 375

*Optional requirements

Table 2 - Chemical Composition and Physical Properties of Fly Ash

Composition and Properties	F Ash	ASTM C618		
		N	F	C
Chemical Composition				
SiO_2, %	49.8	--	--	--
Al_2O_3, %	23.9	--	--	--
Fe_2O_3, %	15.9	--	--	--
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	89.6	≥ 70.0	≥ 70.0	≥ 50.0
CaO, %	5.3	--	--	--
MgO, %	0.7	--	--	--
SO_3, %	0.8	≤ 4.0	≤ 5.0	≤ 5.0
$Na_2O + 0.658K_2O$, %	2.0	--	--	--
Available $Na_2O + 0.658K_2O$, %	0.6	≤ 1.5	≤ 1.5	≤ 1.5
Moisture Content, %	0.7	≤ 3.0	≤ 3.0	≤ 3.0
Loss on Ignition, %	1.3	≤ 10.0	≤ 6.0	≤ 6.0
Physical Properties				
Density, g/cm^3	2.14	--	--	--
Fineness, m^2/kg, by air permeability test method	2650	--	--	--
Fineness, Amount retained on No. 325 sieve, %	33	≤ 34	≤ 34	≤ 34
Strength activity index: With portland cement, at 7 days, % of control With portland cement, at 28 days, % of control	86 93	≥ 75 ≥ 75	≥ 75 ≥ 75	≥ 75 ≥ 75
Water requirement, % of control	97	≤ 115	≤ 105	≤ 105
Soundness: Autoclave expansion or contraction, %	-0.02	≤ 0.8	≤ 0.8	≤ 0.8

*Optional requirement

Table 3 - Mixture Proportion and Properties of Fresh Concrete

Mix No.	Quantities, kg/m^3															
	A0	A1	A2	A3	B0	B1	B2	B3	C0	C1	C2	C3	D0	D1	D2	D3
Cement	429	427	426	421	362	361	361	359	298	296	298	298	234	232	232	231
Fly ash	0	0	0	0	79	79	79	79	160	160	160	161	240	237	237	236
Sand	720	611	499	389	677	574	477	375	642	548	444	346	607	507	406	304
Glass	0	99	197	292	0	98	196	295	0	97	195	293	0	97	193	291
Stone	1079	1073	1071	1059	1073	1071	1071	1067	1069	1064	1070	1072	1073	1064	1064	1059
Water	178	173	174	176	179	178	177	177	177	174	171	173	174	174	175	175
W/Cm	0.42	0.41	0.41	0.42	0.41	0.41	0.40	0.40	0.39	0.38	0.37	0.38	0.37	0.37	0.37	0.37
Unit Weight, Kg/m^3	2406	2384	2367	2337	2371	2363	2362	2353	2346	2338	2337	2343	2329	2312	2308	2295
Slump, cm	8 1/2	7	6 1/2	7	6 1/2	8 1/2	4 1/2	5 1/2	9	9	7 1/2	7	8 1/2	9	7 1/2	7 1/2
Air Content, %	1.4	1.8	1.8	2	1.4	1.3	1.4	1.5	1.1	1.1	1.4	1.5	1.3	1.6	1.4	1.6

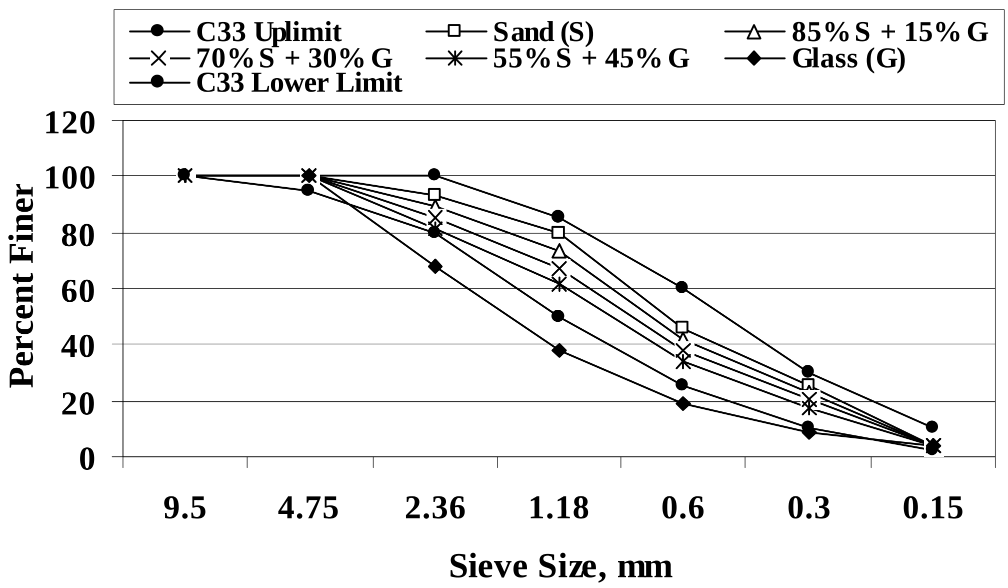

Fig. 1- Gradation of Fine Aggregate

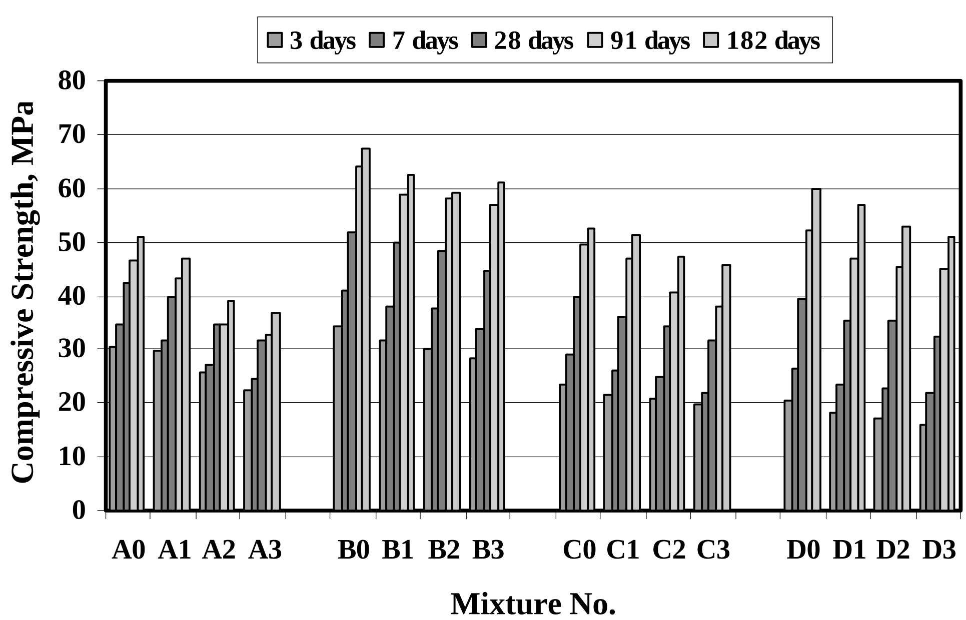

Fig.2 - Compressive Strength Development of Concrete

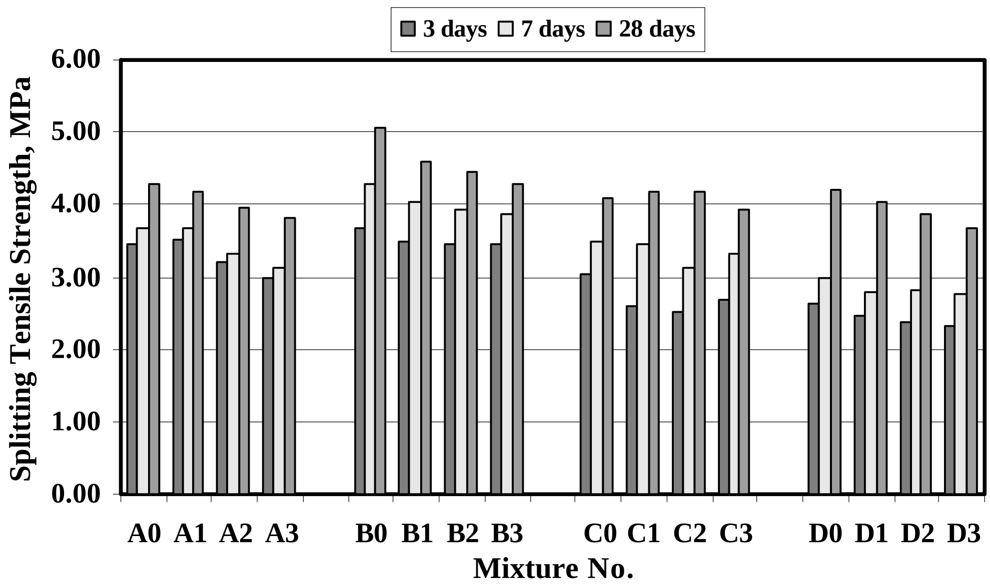

Fig. 3 – Tensile Strength Development of Concrete

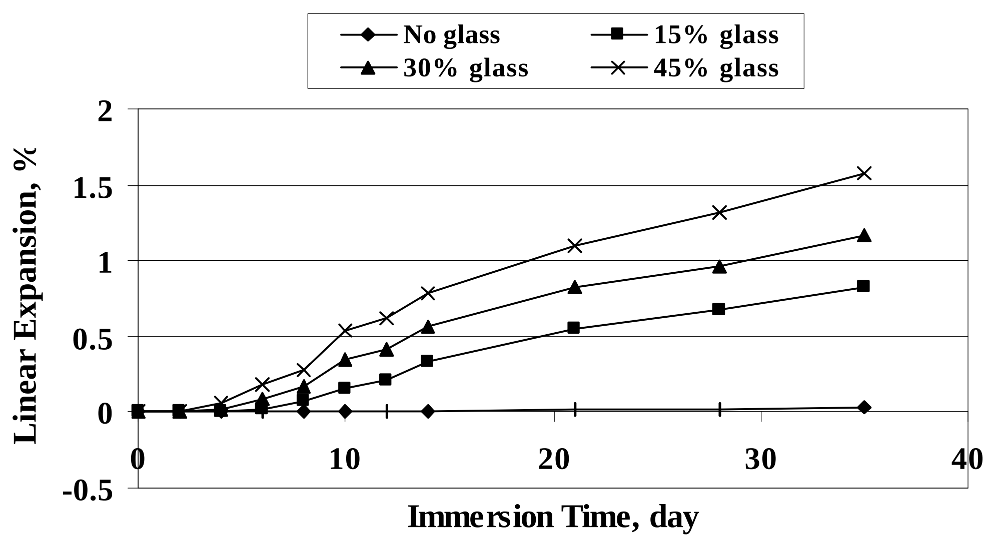

Fig. 4 - Linear Expansion of Mortar Bar in 1.0 N Alkali Solution, without Fly Ash

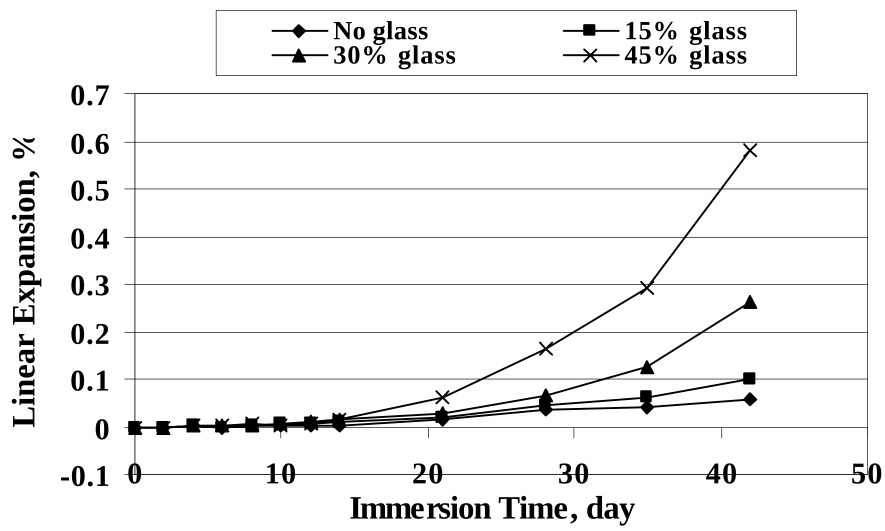

Fig. 5 – Linear Expansion of Mortar Bar in 1.0 N Alkali Solution, with 15% Fly Ash

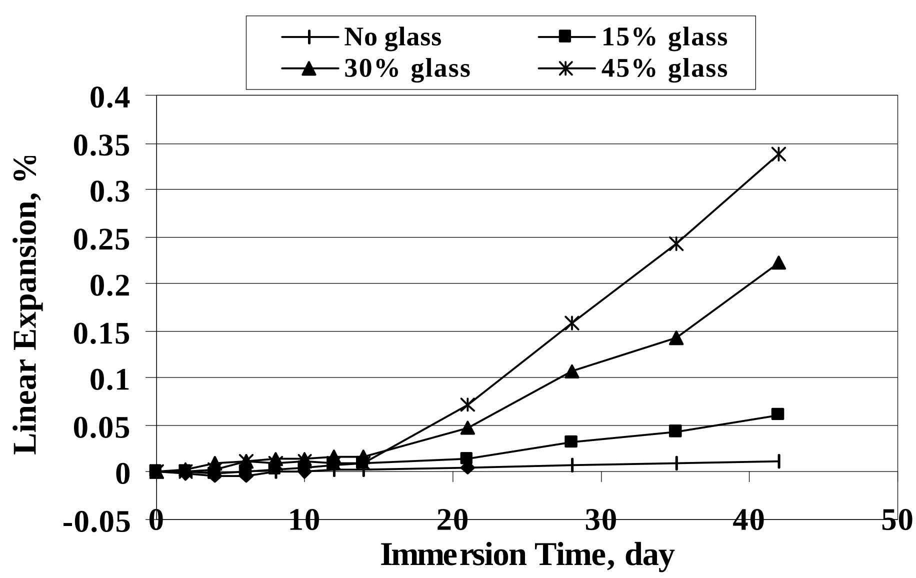

Fig. 6 - Linear Expansion of Mortar Bar in 1.0 N Alkali Solution, with 30% Fly Ash

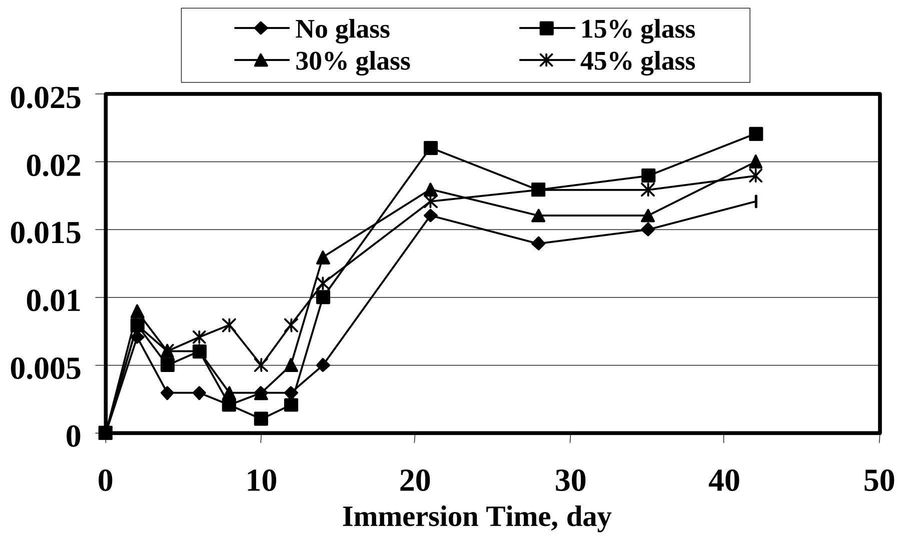

Fig. 7 - Linear Expansion of Mortar Bar in 1.0 N Alkali Solution, with 45% Fly Ash

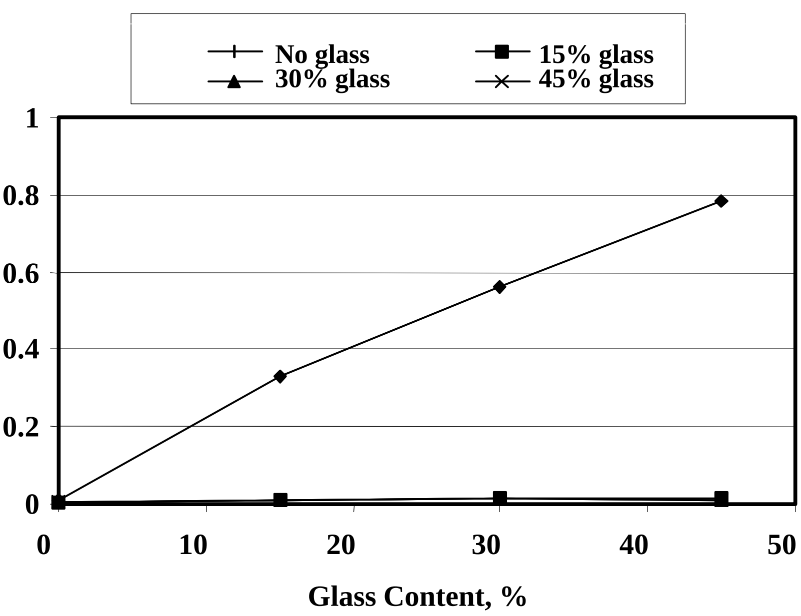

Fig. 8 – Linear Expansion versus Glass Content at 14 Days

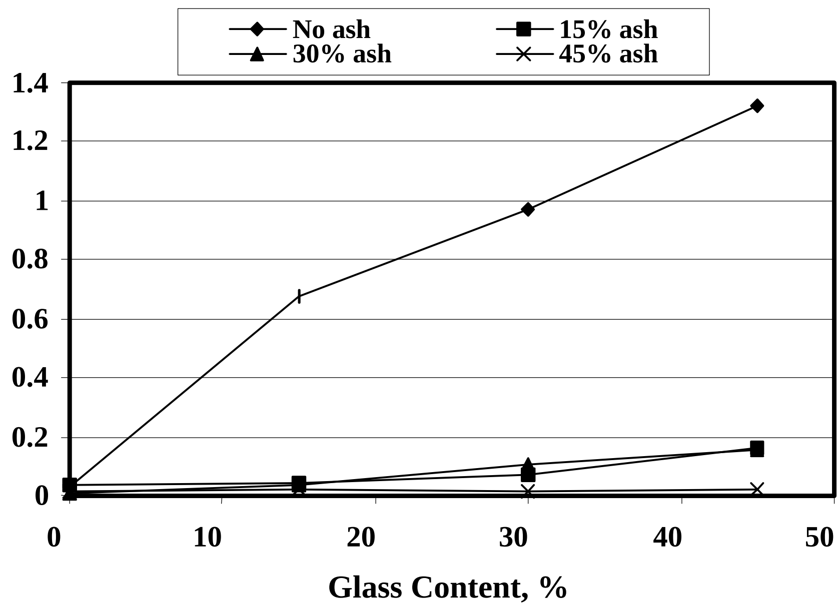

Fig. 9 – Linear Expansion versus Glass Content at 28 Days

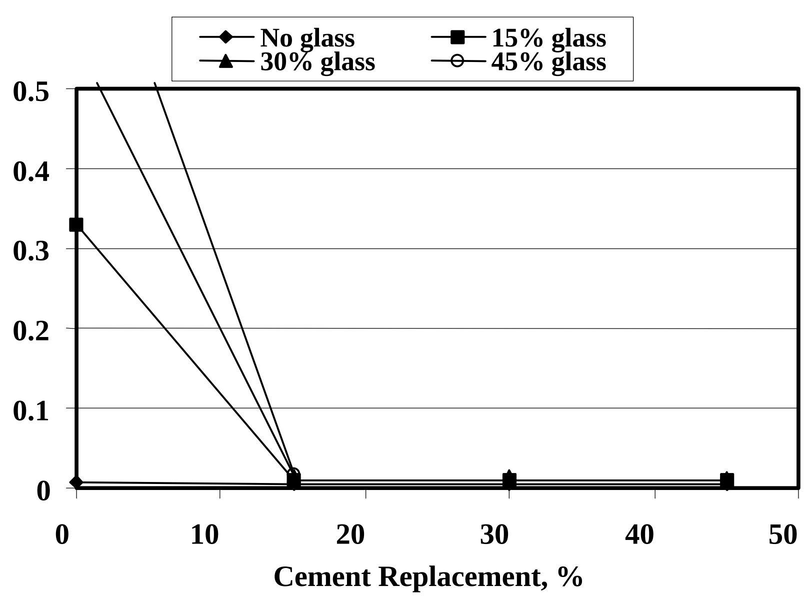

Fig. 10 – Linear Expansion versus Cement Replacement at 14 Days

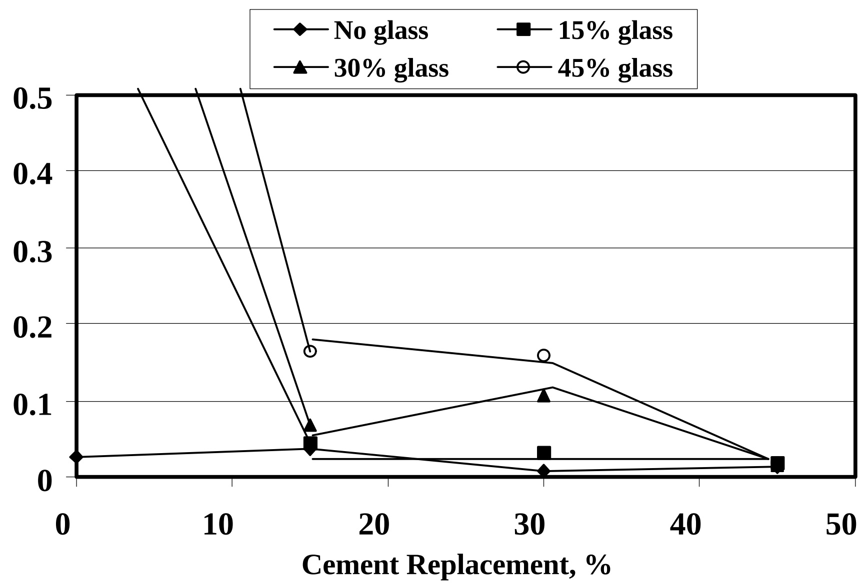

Fig. 11 – Linear Expansion versus Cement Replacement at 28 Days