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Assessing the Effectiveness of Fly-Ash in Mitigating the Alkali-Silica Reaction in Concrete with Soda-Lime Glass

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Abstract: Waste soda lime glass was utilized as a component in concrete mixture replacing coarse aggregates at varying percentages. The use of solid wastes as an alternative component in concrete production is one possible innovative effort to alleviate disposal problem, reduce environmental degradation and reduce the production cost of concrete products. However, one drawback of the use of soda-lime glass in the concrete mix is its ability to produce alkali-silica reaction (ASR). Class-F fly ash was added in the mix as supplementary cementitious material replacing 30% of cement by volume. The potential alkali-silica reactivity (ASR) of concrete with soda-lime glass was determined and the effectiveness of fly ash as a mitigating agent of ASR was evaluated. Test results showed that the replacement of soda-lime glass to coarse aggregates produced an increase in compressive strength of concrete up to 30% replacement. An empirical model was formulated to predict the compressive strength at percentage substitution of soda-lime glass to coarse aggregates. From flexural strength test, results showed that there is a minimal reduction in the flexural strength of concrete as the percentage replacement of soda-lime glass was increased but the reduction can be considered as insignificant. Concrete beam specimens with soda-lime glass experienced a reduction in ductility as manifested by the stress-strain behavior. With the use of class F fly-ash as supplementary cementitious material replacing 30% of cement, the utilization of soda-lime glass can be maximized up to 30% substitution to coarse aggregate without deleterious expansion. Class F fly-ash in moderate level was proven as an effective mitigating agent of ASR in concrete production up to 30% substitution of soda-lime glass to coarse aggregate.

Key Words: alkali-silica reaction; compressive strength; flexural strength; concrete

1. INTRODUCTION

The boom in construction industry results in high demand for concrete since this is one of the most widely used building material. This can lead to exploitation and depletion of natural resources which are the main source of raw materials in concrete production. Aggregates used in the concrete mixture are obtained from crushing and processing of hard rocks or from extracting and screening of unconsolidated deposits of sand and gravel. On the other hand, the production of cement, a component in concrete, produces carbon emission to the atmosphere that greatly contributes to global warming.

The disposal of solid wastes generated by various commercial establishments and households are becoming more difficult through time due to limited availability of space for sanitary landfill, especially in urban areas. In Metropolitan Manila, 5,800 tons of solid wastes are generated per day and seventy-five percent (75%) of which are household wastes. Of the household wastes, nine percent (9%) are glass (Bennagen, 2011). Improper disposal of waste glass causes negative effects on the environment as this can block the sewerage system that could lead to flooding. Recycling waste glass can help address disposal problem, however, glass manufacturing process releases air-polluting compounds like nitrogen oxides, sulfur dioxide and particulates which are harmful to the environment and the health of the population (Talapalariu, 2008). The use of solid wastes as an alternative component in concrete production is one possible innovative effort to alleviate disposal problem, reduce environmental degradation and reduce the production cost of concrete products.

Researches on the innovative use of waste materials in the construction industry have gained the interest of several researchers. A by-product of steel processing called steel slag was ground into sizes to replace coarse aggregates in concrete (Tran et al., 2014). Ground plastics and glass were used to replace up to 20% of fine aggregates in concrete mixes, while crushed concrete was used to replace up to 20% of coarse aggregates (Malek et al., 2007). Ground fine glass powder was incorporated into concrete as pozzolanic material and coarser glass particles as aggregates (Shayan, 2004). Some applications of waste glass in the construction industry are road construction aggregates, asphalt paving component and concrete aggregates (Rindl, 1998). Several studies have shown that soda-lime glass is a potential substitute for aggregates in concrete production. However, one drawback of the use of soda-lime glass in the concrete mix is its ability to produce alkali-silica reaction (ASR). Glass, which is roughly 75 % silica, when mixed with water reacts with the alkali of Portland cement and produces a gel. This gel increases in volume as it absorbs water and this causes expansion cracks and shortens the service life of concrete products. This is one factor that can affect the compressive strength and flexural strength of reinforced concrete. ASR can occur possibly years after the concrete has been placed. To reduce the deleterious effect of ASR, an admixture with pozzolanic properties has to be added in the concrete mixture. Low-calcium (Class F) fly ash, a by-product of burning anthracite or bituminous coal, has pozzolanic properties and is a viable replacement of cement in concrete at 20% to 30% of total cementitious materials (Thomas, 2007).

This study investigates the effect of a combined mixture of waste soda-lime glass and class F fly-ash on the mechanical properties of reinforced concrete. The soda-lime glass was used as a partial substitute for coarse aggregates in a concrete mix with fly-ash as supplementary cementitious materials. The study aims to determine the percentage replacement of soda-lime glass to coarse aggregates with fly-ash that will produce the optimum compressive strength and flexural strength with ASR at tolerable value. The study also investigates if the addition of fly-ash in the concrete mix with soda-lime glass is capable of controlling the expansion cracks due to ASR.

2. EXPERIMENTAL PROGRAM

In the concrete mixture, the coarse aggregates (gravel) were replaced by the soda-lime glass using the percentage replacement by volume of 10%, 20%, 30%, and 40%. Specimens with 0% substitution (no soda-lime glass) were prepared as a control specimen with the target compressive strength of 21 MPa. Class F fly-ash was added in the mix as supplementary cementitious material replacing 30% of cement by volume. Water-cement ratio was set to 0.4 with the required slump of 50mm to 100mm. A typical concrete batch mix proportion is shown in Table 1. A total of seventy-five (75) concrete cylindrical specimens with dimensions of 150mm diameter by 300 mm high were subjected to compressive strength test following ASTM C39. Fifteen (15) reinforced beam specimens, 150x250x1500mm in dimensions, were subjected to flexural strength test subjected to third-point loading in accordance with ASTM C78. Test for expansion was performed in accordance with the procedures set by ASTM C1260 on 20x20x100mm mortar bars to determine the potential alkali-silica reactivity of soda-lime glass. Expansions greater than 0.20% are indicative of potentially ASR reactive aggregates that can result in deleterious expansion and would require a mitigating agent.

Table 1. Typical concrete batch mix proportion

	Percentage (%) Substitution of Glass to Coarse Aggregates (by volume)				
	0%	10%	20%	30%	40%
Cement (kg)	8.4	8.4	8.4	8.4	8.4
Sand (kg)	22.5	22.5	22.5	22.5	22.5
Gravel (kg)	33.75	30.38	27.00	23.63	20.65
Soda-lime glass (kg)	0.0	2.89	5.78	8.68	11.57
Class-F Fly Ash (kg.)	4.8	4.8	4.8	4.8	4.8

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

Table 2 shows the mean compressive strength at every curing period for each percentage substitution. Specimens are considered to have developed an early strength since the compressive strength attained at 7th-day curing period was more than the target strength which was 21 MPa. In a plot of compressive strength against curing period as shown in Fig. 1, it can be observed there is an increasing trend in the strength development and the 30% percent substitution produced the maximum compressive strength values. The combined mixture of soda-lime glass, as a replacement to coarse aggregates, with fly ash produced positive results up to 30% replacement. At the 28th day curing period, the compressive strength was greater by almost 13% than the compressive strength of the control specimen. However, when substitution reached 40%, the compressive strength was lower than the controlled specimen. Soda-lime glass having a smoother surface and lighter weight resulted in the weak bond between aggregate and cement and therefore resulted to lower compressive strength. This was attested by the mode of failure observed from the specimen as shown in Fig. 2. The specimen showed interfacial cracks and failed by axial splitting which implies that the specimen is subjected to a stress state along the vertical plane and fails due to the lack of sufficient frictional resistance between the particles. When a lightweight aggregate is used, just like the soda-lime glass, the axial splitting of the aggregate will prevail (Van Mier, 1998).

Table 2 Mean compressive strength at the curing period

% Substitution of Glass to Coarse Aggregates	Compressive Strength (MPa)		
	7th day	14th day	28th day
0	23.96	29.70	31.91
10	26.84	29.68	34.78
20	26.18	29.70	35.09
30	26.25	30.93	36.01
40	19.15	23.23	24.69

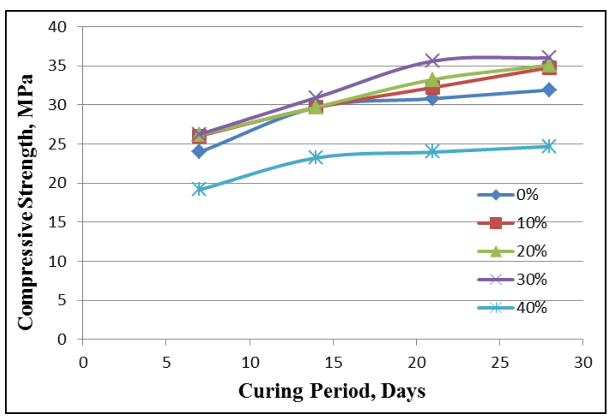

Figure 1 Compressive strength development against curing period

Statistical analysis using One-Way Analysis of Variance (ANOVA) was performed to analyze the variance of experimental data and to determine if the substitution of coarse aggregate with soda-lime glass has a significant effect on the compressive strength. The analysis yielded a *p*-value less than 0.05 which means that at the 95% significance level, there is a significant effect in the compressive strength of concrete when the soda-lime glass is used as a coarse-aggregate substitute.

Figure 2 Mode of failure of cylindrical specimen

The compressive strength for each percentage substitution is presented in a normalized form by dividing the experimental data with the compressive strength of the control specimen. Figure 3 shows the normalized graph of the compressive strength against the percentage of soda-lime glass substitution. The data points were plotted in a scattered matter and yielded a trend line equation in the form,

$$fc_x = \left(-188.88x^4 + 124.73x^3 - 26.354x^2 - 2.132x + 1\right)fc_o \quad \text{(Eq. 1)}$$

where:

fc_x = compressive strength of concrete with x% soda-lime glass content

fc_o = compressive strength of control specimen (0% soda-lime glass)

x = soda-lime glass substitution (in decimal form, i.e 20% is 0.20)

The trend line equation has a coefficient of determination, R^2 = 0.931; this indicates that the model fits the data well. From the equation obtained, the soda-lime glass percentage substitution to coarse aggregate that will produce the highest compressive strength is at 31%.

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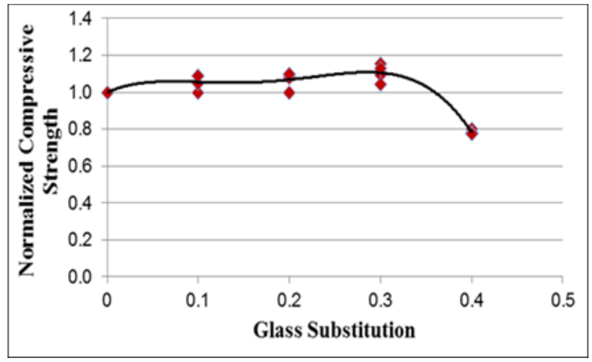

Figure 3 Normalized compressive strength against soda-lime glass substitution

3.2 Flexural Strength

The modulus of rupture of concrete represents its flexural strength. It is the capacity of concrete to resist failure in bending. Table 3 shows the flexural strengths obtained from the flexural strength test subjected to third-point loading. The mean flexural strength was plotted against the percentage of soda-lime glass substitution as shown in Figure 4. A downward trend can be observed from the graph, which implies that using glass as coarse aggregates decreases the flexural strength of the reinforced beam samples. The decreased in strength can be attributed to the smooth surface texture of the soda-lime glass. The smooth texture of aggregate results to the weaker bond between the concrete paste and the aggregates thus leads to lower strength (Adajar et al., 2017).

Table 3 Flexural strength of concrete beam specimens

% Substitution of Glass to Coarse Aggregates	0%	10%	20%	30%	40%
Flexural Strength (MPa)	11.60	11.83	11.49	11.31	11.65
	11.83	11.36	11.75	11.43	11.32
	11.63	11.54	11.31	11.60	10.93
Mean	11.69	11.58	11.51	11.44	11.30

To test whether the observed decrease in flexural strength at different percent substitution is significant, analysis of variance (ANOVA) was performed. The result yielded a *p*-value greater than 0.05 which means that the substitution of glass to coarse aggregate has no significant effect on the flexural strength of the concrete at a 95% significance level.

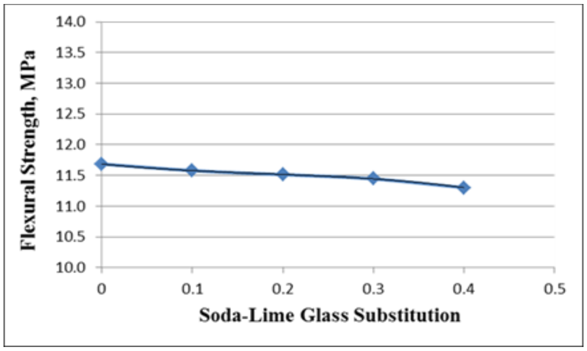

Figure 4 Mean flexural strength against soda-lime glass substitution

Data gathered from flexural strength tests were used to plot the stress-strain diagram of the reinforced beam specimens and to describe their behavior when subjected to increasing loads. Figure 5 presents the stress-strain diagram of the reinforced beam specimens. It can be observed that the control specimen achieved its yield strength at greater strain while specimens with soda-lime glass achieved the yield strength at the lower strain. This indicates that a reduction in ductility was experienced when the soda-lime glass was used in the concrete mix. This is not a desirable property of structural member since the structure is usually designed to behave in a ductile manner where it will undergo large deformation without rupture before failure. It is necessary that structure provides not only sufficient strength but also adequate flexural ductility to ensure that occupants of the structure are given enough warning and sufficient time to take preventive measures before failure occurs.

3.3 Alkali-Silica Reaction

Figure 6 displays the expansion in length of the mortar bars soaked at 1M of NaOH solution for curing period of 2 weeks (14 days). It is evident that sample with 0% glass substitution had the least expansion (0.097%) while the samples with 40% glass substitution had the greatest amount of expansion (0.3277%).

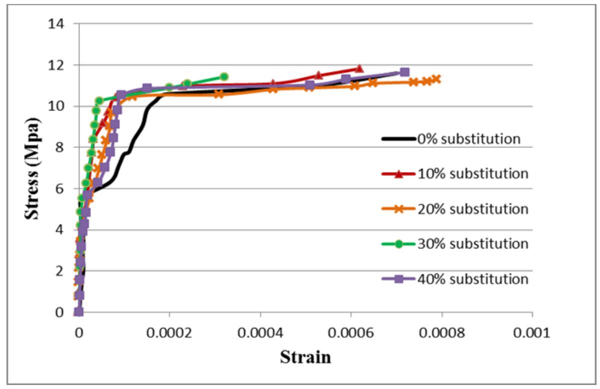

Figure 5 Stress-strain behavior of reinforced beam specimens

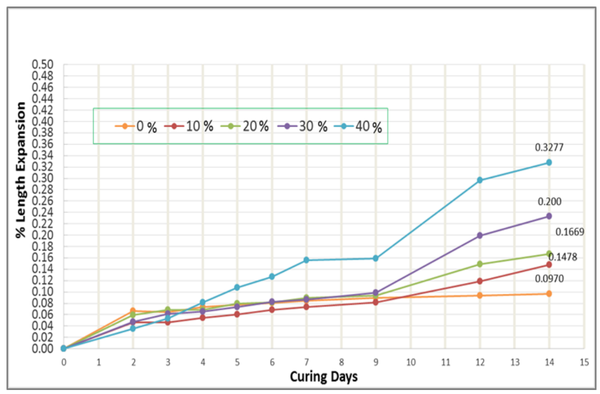

Figure 6 Length of expansion for every curing period

In Figure 7, the length of expansion is presented for every percentage of glass substitution. It can be noted that as the amount of glass increases, the amount of length expansion also increases. The mixture with more than 30% soda lime glass exceeds the expansion criteria, thus it can be concluded that the specimen contains a potentially ASR reactive aggregates. From test results, it has been found that the fly ash proved to be effective in mitigating the effects of ASR up to 30% partial replacement of the soda-lime glass to coarse aggregate. Using more than 30% of soda-lime glass as a substitute for coarse aggregate resulted to expansion greater than 0.20% which means that the mixture is potentially ASR reactive and fly-ash is ineffective in mitigating the effects of ASR.

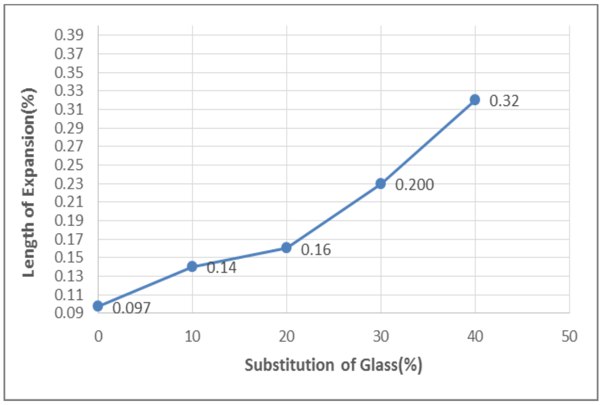

Figure 7 Length of expansion at every % of glass substitution

4. CONCLUSIONS

Based on test results, the following conclusions were drawn:

The combined mixture of soda-lime glass, as a replacement to coarse aggregates, with fly ash produced positive results in the compressive strength up to 30% replacement. Maximum compressive strength was achieved at 30% glass substitution. Using the developed empirical equation, the optimum compressive strength can be obtained at 31% soda-lime glass substitution to coarse aggregates.

There is a minimal decrease in flexural strength as more glass substitution was added in the concrete mix, however, the reduction is considered as insignificant based on statistical analysis. Yield strength was achieved at lower strain, indicating reduced ductility on the concrete sample.

Expansions of the samples with soda-lime glass were noted but with the use class F fly-ash as supplementary cementitious material replacing 30% of cement, the utilization of glass can be maximized up to 30% substitution for coarse aggregate without deleterious expansion.

Waste soda-lime glass is a viable replacement for coarse aggregate in concrete production up to 30% substitution with class F fly-ash in moderate level as supplementary cementitious materials without compromising the structural integrity and quality of the finished concrete products.

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