ASSESSING THE MECHANICAL PROPERTIES OF CONCRETE DUE TO ALKALI SILICA REACTION

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ABSTRACT

The aim of this paper is to examine and validate the mechanical properties of concrete damaged by Alkali Silica Reaction (ASR). ASR was initiated by using fused silica as a reactive aggregate and increasing the alkali level of the concrete. The concrete was stored under controlled environment of 38°C and 100% RH for a period of one year. Over this time period, the strength of ASR concrete decreased by 40%, and the modulus of elasticity and modulus of rupture by 77% from their initial values. The expansion of the ASR concrete affects its mechanical properties which deteriorate as the concrete expands, and stabilised when the concrete ceases to expand. The initial properties of ASR concrete were validated by examining separately the effect of individual ASR-inducing parameters on the properties of normal concrete. It was confirmed that adding alkali in the normal concrete mixture reduces the initial strength of the concrete, but it increases the modulus of elasticity. Fused silica did not affect the initial strength of normal concrete, but the modulus of elasticity was affected by the amount of fused silica present in the concrete. Neither fused silica nor additional alkali affects the modulus of rupture of the normal concrete.

Keywords: Alkali Silica Reaction, fused silica, mechanical properties, strength, modulus of elasticity, modulus of rupture.

1. INTRODUCTION

Alkali Silica Reaction (ASR) is a reaction that occurs between siliceous aggregate such as opal and chert with high alkali cement in concrete. Depending on the amount of reactive aggregate and alkali, the reaction causes concrete to expand which continues until one or both components are consumed. Under ambient environment, the reaction is very slow.
However, an increase in the temperature and humidity of the environment accelerates the reaction, resulting in notable expansion in a short time. As proposed by the ASTM C1293 (concrete prisms test), the expansion of concrete can be measured periodically in a year under sealed conditions of 38°C and 100% humidity.

When the expansion exceeds the tensile strain capacity of the concrete, development of cracking affects the mechanical properties of the concrete, particularly the modulus of elasticity and modulus of rupture. To study the effects of ASR in concrete, the choices of reactive aggregate are vast but natural aggregate are not sufficiently uniform for this purpose. Swamy and Al-Asali [1] indicated that Pyrex produced too much expansion in concrete, and they recommended the use of fused silica to study the effect of ASR. An amount of 15% fused silica present in the concrete can produce a maximum expansion of 6000 microstrain within a year. The limit of the study was between 15% and 20% fused silica. This pessimum content of 15% fused silica was also used by other researchers to study the effect of ASR on the properties of concrete [2,3].

In this paper, a repeatable study of the effect of ASR on concrete made with fused silica is presented. Various percentages of fused silica in the range of 3% to 20% were used in the study to assess the expansion as well as the mechanical properties of the concrete. This paper also places emphasis on the effect of individual ASR-inducing components on the initial properties of normal concrete.

2. EXPERIMENTAL WORK

2.1 Test program

The experimental program can be divided into two groups. Group 1 studies the effect of various percentages of fused silica on the expansion and mechanical properties of concrete, while Group 2 supports the findings of Group 1 by examining the effect of individual ASR-inducing components on the mechanical properties of normal concrete.

2.2 Concrete mixture

All tests in this study were conducted according to ASTM C1293 Standard - Determination of length change of concrete due to Alkali Silica Reaction. Only one concrete mix was used with a ratio of 1:1.5:2.7 (cement: sand: coarse aggregate), a cement content of 420 kg/m³ and a water-cement ratio of 0.44. The cement used was GP cement having an alkali content of 0.43% Na₂O equivalent. To obtain significant expansion, sodium hydroxide was added in the mixing water to increase the level of cement alkali to 1.25% Na₂O equivalent. Fused silica replaced the fine aggregate by 3%, 7.5%, 10%, 15% and 20% by mass of the total aggregate content. The course aggregate used was a non-reactive basalt.

2.3 Dimensions and exposure conditions

Concrete expansion was measured on 75x75x285 mm prisms with a steel stud fixed at both ends of the prism. The strength and modulus of elasticity of the concrete were obtained on cylinder of 100mm diameter and 200mm height. The tensile strength of concrete was measured on 100 x 100 x 350 mm beams. All specimens were stored in an environmental tank closely controlled at 38°C ± 2°C and 100% relative humidity above the water.
2.4 Test measurement

All tests in these experiments were conducted at 7 days, 28 days, 3 months, 6 months and 12 months of exposure in the environmental tank. The expansion of the concrete prisms at each age was measured using a digital gauge and calculated with respect to initial length reading.

The strength of the concrete is calculated by dividing the ultimate load by the area of the cylinders. The modulus of elasticity was determined using 40% of the ultimate load and strain readings of the gauges attached to the concrete surface at two opposite locations. For modulus of rupture of concrete beam, reloaded under four points at the rate of 0.5mm/second and the modulus of rupture of the concrete was obtained by the following formula:

\[ f_i = \frac{PL}{bd^2} \ (N / mm^2) \]

where, \( P \) is the maximum applied load (N), \( L \) is the distance between knife edges on which the sample is supported (mm), and \( d \) is the width and depth of the specimen (mm).

3. TEST RESULT

3.1 Expansion of ASR concrete

Fig.1 shows the expansion of the concrete made with various percentages of fused silica from the experiment Group 1. The level of expansion of ASR concrete at the beginning and at the end of the exposure periods depends on the amount of fused silica present in the concrete as the amount of alkali is the same for all concrete. At the beginning of the reaction, an increase in the amount of fused silica produces higher levels of expansion, but concrete with this amount of fused silica achieved early stabilization, with an expansion level less than that for the concrete with a small amount of fused silica. For example, the expansion of the concrete with 20% fused silica was 0.9%, being 25% less than that of the concrete with 3% fused silica. There is a clear difference in the expansion curve between the concrete with 3% fused silica and the other concretes, showing that the expansion of the former concrete did not cease at the end of one year. In fact, this concrete had a higher expansion level when measurement was extended beyond a year. According to the ASTM C1293, the reactivity of concrete is confirmed if the level of expansion exceeds 0.04% in a year. All the ASR concretes exceed this limitation in only 1 or 2 weeks. The pessimum content of fused silica to give the highest expansion in a year was 7.5%.
Figure 1: Expansion curves of ASR concrete with various percentages of fused silica over time

Table 1: Group 1 (ASR concrete)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3% fused silica + alkali</td>
</tr>
<tr>
<td>B</td>
<td>7.5% fused silica + alkali</td>
</tr>
<tr>
<td>C</td>
<td>10% fused silica + alkali</td>
</tr>
<tr>
<td>D</td>
<td>15% fused silica + alkali</td>
</tr>
<tr>
<td>E</td>
<td>20% fused silica + alkali</td>
</tr>
</tbody>
</table>

Table 2: Group 2 (ASR individual component)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Normal concrete</td>
</tr>
<tr>
<td>II</td>
<td>Normal concrete + additional alkali</td>
</tr>
<tr>
<td>III</td>
<td>Normal concrete + 3% fused silica Normal concrete + 10% fused silica Normal concrete + 20% fused silica</td>
</tr>
</tbody>
</table>
3.2 Mechanical properties of ASR concrete

The changes in the properties of ASR concrete are assessed in relation to the time of exposure and the expansion of the concrete. The results are described below.

3.2.1 Time dependence of the mechanical properties of ASR concrete

The results of the strength testing of ASR concretes conducted periodically for 48 weeks are shown in Table 3 and graphically presented in Fig. 2. The strength of ASR concrete gradually decreases over time between 5-11% after 4 weeks and between 26-33% after 12 weeks from its initial strength. The result shows that there is not a strong correlation between the amount of fused silica and the strength of the concrete especially at the final measurement. Generally speaking, the strength of the ASR concrete stabilised after 24 weeks, with a little increase or decrease in strength after that.

![Figure 2: Relative compressive strength of concrete with various percentages of fused silica](image)

**Table 3: Strength of ASR concrete (N/mm²)**

<table>
<thead>
<tr>
<th>Time (Week)</th>
<th>3%</th>
<th>7.5%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38.6</td>
<td>34.4</td>
<td>37.3</td>
<td>38.1</td>
<td>37.7</td>
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<tr>
<td>4</td>
<td>35.8</td>
<td>32.9</td>
<td>33.1</td>
<td>34.9</td>
<td>35.5</td>
</tr>
<tr>
<td>12</td>
<td>25.9</td>
<td>25.3</td>
<td>25.3</td>
<td>25.9</td>
<td>28.0</td>
</tr>
<tr>
<td>24</td>
<td>22.4</td>
<td>21.7</td>
<td>18.1</td>
<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>48</td>
<td>21.6</td>
<td>23.9</td>
<td>19.3</td>
<td>27.4</td>
<td>26.0</td>
</tr>
</tbody>
</table>
Table 4 and Fig. 3 present the test result for modulus of elasticity of ASR concrete conducted periodically for 48 weeks. Initially, an increase in the amount of fused silica produced a lower modulus of elasticity especially at the early age. For example, the concrete with 3% fused silica had a modulus of elasticity of 29,054 N/mm$^2$ and concrete with 20% fused silica had a modulus of elasticity of 19,007 N/mm$^2$. A significant reduction in modulus of elasticity was recorded for all concretes after 4 weeks, with a loss of about 53% from its initial values. As the concrete aged, the modulus of elasticity continued to drop – up to about 80% from its initial value. Fluctuation in the modulus of elasticity was found on some ASR concrete after that significant reduction. Generally, the modulus of elasticity stabilised after 24 weeks, with little increase or decrease in the value afterwards. A reduction in the modulus of elasticity at the end of the exposure period also depended on the amount of fused silica in the concrete, with a greater reduction recorded for the concretes containing larger amounts of fused silica.

![Figure 3: Relative modulus of elasticity with various percentages of fused silica](image)

Table 4: Modulus of elasticity of ASR concrete (N/mm$^2$)

<table>
<thead>
<tr>
<th>Time (Week)</th>
<th>3%</th>
<th>7.50%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29054</td>
<td>25786</td>
<td>21234</td>
<td>20120</td>
<td>19007</td>
</tr>
<tr>
<td>4</td>
<td>12253</td>
<td>11730</td>
<td>11249</td>
<td>9298</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>6111</td>
<td>4490</td>
<td>3959</td>
<td>6233</td>
<td>11380</td>
</tr>
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<td>4700</td>
<td>5287</td>
<td>4970</td>
<td>8146</td>
<td>9055</td>
</tr>
<tr>
<td>48</td>
<td>6201</td>
<td>6995</td>
<td>5784</td>
<td>8797</td>
<td>9461</td>
</tr>
</tbody>
</table>

The results of the modulus of rupture test are shown in Table 5 and graphically presented in Fig. 4. A smaller amount of fused silica gave a higher initial modulus of rupture. For example, the concrete made with 3% fused silica had a modulus of rupture of 5.6 N/mm$^2$, while the concrete made with 20% fused silica had a modulus of rupture of 3.4 N/mm$^2$. As the concrete aged, the modulus of rupture continued decreased, but this had no correlation with the amount of fused silica in the concrete. Fluctuations in the modulus of rupture of the
concretes were found after a significant loss in the property. Generally, at the end of the exposure period, the reduction in the modulus of rupture was greater when the concrete had a higher initial modulus of rupture.

![Figure 4: Relative modulus of rupture of concrete with various percentages of fused silica](image)

Table 5: Modulus of rupture of ASR concrete(N/mm²)

<table>
<thead>
<tr>
<th>Time (Week)</th>
<th>3%</th>
<th>7.5%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.6</td>
<td>5.8</td>
<td>4.6</td>
<td>3.6</td>
<td>3.4</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
<td>2.1</td>
<td>1.5</td>
<td>1.4</td>
<td>2.0</td>
</tr>
<tr>
<td>12</td>
<td>1.3</td>
<td>1.2</td>
<td>1.0</td>
<td>1.4</td>
<td>2.4</td>
</tr>
<tr>
<td>24</td>
<td>1.6</td>
<td>1.1</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>48</td>
<td>1.4</td>
<td>0.5</td>
<td>1.9</td>
<td>1.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>

As all the concrete underwent significant expansion with time, the losses of mechanical properties are considered to be related to the observed expansion level.

3.2.2 Expansion dependence of the mechanical properties of ASR concrete

The development of expansion with time demonstrated that the rate of expansion was rapid between 1-12 weeks occurred rapidly and after that, the expansion rate reduced and stabilised. To correlate the expansion with the loss in the mechanical properties of ASR concrete, three types of ASR concretes made with 3%, 10% and 20% fused silica were further analysed. As shown in Fig.5, the initial strength of ASR concrete was not affected by the expansion that occurs in the concrete. The concrete made with 3% fused silica had negative expansion at the beginning of measurement, while the concrete made with 20% fused silica expanded at about 0.06%. Even though the expansion level for concrete made with 20% fused silica was high, it did not change the initial compressive strength of the concrete. As the expansion continued, the compressive strength of the concretes reduced. However when the expansion stabilised, the compressive strength remained unchanged.
As for the modulus of elasticity and modulus of rupture, the initial value of ASR concrete depends not just on the amount of fused silica but also on the level of expansion that occurred in the concrete. Fig. 6 and 7 shows the relationship between the modulus of elasticity and the modulus of rupture of ASR concrete with the level of expansion. The concrete made with 3% fused silica exhibited expansion small contraction at the beginning, resulting in a higher modulus of elasticity and modulus of rupture. The concrete made with 20% fused silica exhibited higher expansion levels and produced smaller values of modulus of elasticity and modulus of rupture. There is an exponential relationship between expansion and the modulus of rupture, and modulus of elasticity especially at the early level of expansion where both properties drop significantly. After that, continued low rate of expansion does not drastically change the modulus.
3.3 The initial properties of ASR concrete

The initial properties of the ASR concrete were measured at 7 days in the environmental tanks. At that time, the levels of expansion varied between the types of ASR concrete. For example, while other ASR concrete made with fused silica started to expand, the concrete made with 3% fused silica exhibited negative expansion, which we can assume was 0. In order to know what exactly affects the initial properties of ASR concrete, the experiment of Group 2 was carried out.

A test of the level of expansion without either one of the ASR-inducing parameters components was carried out to determine if the component contributes to the expansion in the concrete. For this purpose, the expansion of normal concrete with additional alkali only was assessed. This enabled a comparison to be made between the expansion of normal concrete and the ASR concrete (with 7.5% fused silica only). Fig.8 plots the expansion of the concrete up to 12 weeks for comparison purposes. As clearly shown in Fig. 5, the expansion of normal concrete with added alkali is relatively small. In fact, the test was continued for one year, and the expansion of this concrete was considered negligible. In addition, no sign of cracking was found in the concrete samples. These findings show that the additional alkali perse does not cause any significant expansion.

With the assumption that the expansion level of the concrete without one of the ASR components was zero for all time, the properties of normal concrete with and without additional alkali and fused silica can be assessed. Fig.9 shows the results of the strength test of strength of normal concrete with and without alkali and fused silica. As shown, additional alkali reduces the strength of the normal concrete by 28% even though it seems that at 48
weeks the strength differences between both types concrete are little. Fused silica did not change the strength of normal concrete up to 8 weeks. This finding suggests that additional alkali in the normal concrete mixture reduces the strength of the concrete.

The modulus of elasticity of the normal concrete with and without alkali and fused silica is shown in Fig.10. Adding alkali into the normal concrete increases the modulus of elasticity of the concrete, however the modulus of elasticity decreases by nearly 20% after 48 weeks. The modulus of elasticity of all normal concretes (no added alkali) with difference percentages of fused silica was similar between 1 and 2 months. The initial modulus of elasticity of the ASR concrete is lower than the normal concrete with fused silica only.

The effect of alkali and fused silica on the modulus of rupture of normal concrete is shown in Fig.11. As shown in the figure, additional alkali increases the modulus of rupture of normal concrete up to 20%. For this study, the modulus of rupture of normal concrete is obtained using the formula \( 0.6\sqrt{f_c} \), where \( f_c \) is the average strength of the cylinder. The modulus of rupture difference between normal concrete with and without alkali is considered small. The presence of fused silica in the normal concrete (no added alkali) does not significantly change the modulus of rupture of the concrete.

This experiment clearly reveals that the effect of ASR-inducing parameters on the expansion and mechanical properties of the normal concrete is not significant.

![Figure 8: Expansion curve of ASR concrete in compared with the expansion of normal concrete with and without alkali](image)
Figure 9: The strength of the normal concrete with and without alkali and normal concrete with fused silica only.

Figure 10: The modulus of elasticity of the normal concrete with and without alkali and normal concrete with fused silica only.
Figure 11: The modulus of rupture of the normal concrete with and without alkali and normal concrete with fused silica only

Figure 12: Comparison of modulus of elasticity between low and high alkali concrete without reactive aggregate
4. COMPARISON WITH OTHER PUBLISHED DATA

Fused silica has been used by some researchers to study ASR in the concrete as it contains 99% silica and no alkali in the aggregate. With the same alkali levels and with the same environmental conditions, the variation in the amount of fused silica present in the concrete affects the level of expansion. The pessimum content of fused silica attributed to the maximum expansion can be achieved by studying the effect of various percentages of fused silica. Contrary to the previous study conducted by Swamy and Al-Asali, which showed that concrete made with 15% fused silica had the largest expansion of 0.875% [1], the current study found that concrete made with 7.5% fused silica experienced the highest expansion level of 1.13%. The difference in the results of the two studies may be related to the nature of the fused silica and Portland cement used.

This study produced results which corroborate the conclusion of research that the strength of the ASR concrete is not a good indicator of assessing the concrete. The initial strength of ASR affected concrete is similar at any expansion level with the similar type of reactive aggregate. This is because, during the compression test, the pre-existing crack due to ASR is closed up and increases the apparent strength of the concrete perpendicular to the load direction compared to bending test [4]. The modulus of elasticity and modulus of rupture are both sensitive to the amount of expansion that occurs in the concrete as a result of the variation in the amount of reactive aggregate in the concrete [5].

Expansion in the concrete is considered negligible if one of the ASR components is not present in the concrete. The present findings seem to be consistent with the conclusion in other research that adding alkali to the normal concrete reduces the strength of the concrete [6,7]. However, an increase in the modulus of elasticity was found with the normal concrete with added alkali especially at 28days, and similar findings were reported with dynamic modulus of elasticity at 14days in concrete with high alkali cement content [8]. Fig.12 compares the effect of added alkali on the modulus of elasticity of the concrete in the current study and in a study done by Smoui et al [9]. While Smouiet al. found no distinct differences between the modulus of elasticity of concrete with 0.6%NaOH and 1.25%NaOH, the current study reveals that over a longer period of time, the modulus of elasticity of the normal concrete with added alkali decreased.

A variation in the percentage of fused silica in the concrete did not affect the strength of normal concrete up to two months. A similar finding was reported using opal without adding alkali into the normal concrete even though a single amount of reactive aggregate was used for the study [7]. The modulus of elasticity is affected by the amount of fused silica used in normal concrete. A similar observation was made for the ASR concrete where the initial modulus of elasticity depended on the amount of fused silica present in the concrete. There was a decrease in the modulus of elasticity when a larger amount of fused silica was present in the normal or ASR concrete.

Separate addition of alkali and fused silica to the normal concrete does not reduce the modulus of rupture of the normal concrete. The reduction in the modulus of rupture of concrete occurs when the ultimate tensile strain is exceeded. As found in the study, the expansion of the normal concrete with added alkali was -3.56x10^-9 which is far smaller than the ultimate strain of concrete. Therefore, the modulus of rupture of the concrete with added alkali is not affected and it is possibly similar to the normal concrete with fused silica only.
5. CONCLUDING REMARKS

The initial strength of ASR concrete with various percentages of fused silica at similar alkali content is the same regardless of the expansion level of the ASR concrete. However, the initial modulus of elasticity and modulus of rupture of ASR concrete depend on the amount of fused silica present in the concrete which affects the expansion of the concrete. Generally, a larger amount of fused silica present in the concrete contributes to a lower modulus of elasticity and modulus of rupture. The subsequent reduction in these properties is smaller for the ASR concrete with a larger amount of fused silica compared with the ASR concrete with the smaller amount of fused silica.

Adding alkali into the normal concrete mixture reduces the initial strength of the concrete, increases the initial modulus of elasticity of the concrete and later gradually decreases the modulus of elasticity. Interestingly, the normal concrete with added alkali does not change the modulus of rupture similarly as the normal concrete.

Adding various percentages of fused silica in the normal concrete does not change the initial strength of the normal concrete up to 2 months. However, the change in the modulus of rupture of the normal concrete with fused silica is largely affected by the amount of fused silica present in the concrete. An increase in the amount of fused silica reduced the initial modulus of elasticity of the normal concrete. Interestingly, the modulus of elasticity does not change for up to 2 months. In terms of the modulus of rupture, fused silica does not change the property at any amount of fused silica and in a period of up to 2 months.

6. ACKNOWLEDGEMENT

The first author thanks The Ministry of High Education Malaysia for assistance in the form of a scholarship to conduct the research. In addition the author would like to thank the Department of Civil Engineering, Monash University in providing laboratory facilities and assistance.

REFERENCES


