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The Influence of Calcined Clay Pozzolan, Low-Cao Steel Slag and Granite Dust On the Alkali-Silica Reaction in Concrete

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Abstract
The influence of low CaO steel slag, calcined clay and granite dust on the alkali-silica reaction was investigated over a period of 35 days under accelerated curing conditions. The mineral admixtures were used to replace varying portions of high alkali Portland limestone cement up to an admixture content of 25% in order to study their effect on the alkali-silica reaction (ASR). Portland limestone cement used for the study had a total Na_2O_{eq} of 4.32. XRD analysis of hydrated mortar bar samples confirmed the formation of an expansive sodium silica gel in the reference Portland cement mortar bar as the agent responsible for ASR. Stable calcium silicates were formed in the mortar bars containing calcined clay in increasing quantities whilst the presence of the sodium silicate gel decreased.The occurrence of these stable silicates in hydrated samples containing steel slag and granite dust was however minimal, compared to calcined clay cement mortars. The highest expansion was recorded for granite dust mortar bars, reaching a maximum of 25.98% at 35 days. Mortar-bar expansion decreased as calcined clay content in the cement increased;mortar bars with 25% calcined clay were the least expansive recording expansion less than 0.1% at all test ages. Whilst the expansion was reduced by between 42.5% and 107.8% at 14 days with increasing calcined clay content, expansion rather increased between 36.8% and 169.5% at 14 days with increasing granite dust content.Steel slag mortar bars experienced reduction in 14 days expansion between 14.3% - 46.2%.The study confirms that steel slag and calcined clay pozzolan have greater influence on ASR in mortar bars than granite dust and shows that calcined clay and low CaO steel slag could be considered as remedial admixtures for ASR at replacement levels of 25% and 15% respectively.

Keywords: low-CaO steel slag, calcined clay pozzolan, granite dust, alkali-silica reaction, expansion, sodium silicate gel, calcium silicates

I. Introduction

Durability of cement products and concrete has received considerable attention within the past decade with many researchers reporting the influence of various deleterious media and chemical phenomena on properties of cement and concrete[1] -[4].One such deleterious chemical phenomenon is the alkali-silica reaction. The alkali-silica reaction (ASR) is a chemical reaction within concrete between reactive siliceous constituents ofcoarse aggregates and the alkali hydroxides released during the hydration of a high alkali Portland cement, with analkali content of over 0.6% [5], in the presence of sufficient moisture [6] [7].

The alkali-silica reaction causes cracking and often severe damage in hardened concrete through swelling of an expansive gel bythe absorption of moisture[8]-[10]. Even though ASR is often only apparent under field conditions after 5 to 15 years and tests such as the 2 year long Canadian CSA A 23.2-14A/28A [11] method exist for ASR evaluation, accelerated methods are commonly employed to rapidly determine the alkali-silica reactivity or otherwiseof aggregates [12]-[14]. According toKandasamy and Shehata[15] whoevaluated the effect of high calcium fly ash/slag ternary blended cements on ASRby both the accelerated mortar bar method of ASTM C 1260 [13] and CSA A 23.2-14A/28A, there is a good agreement between the results of the twotest methods. They concluded that ASTM C 1260 provided a conservative evaluation of the ability of the supplementarycementitious materials studied to mitigate ASR.

The incorporation of mineral admixtures in Portland cement manufacture is favoured not only due to energy savings and reduction in greenhouse gas emissions[16], mineral admixtures are also known to influence significantly the resistance of concrete and other cement products to deleterious chemical reactions [17]. Mineral admixtures recommendedinclude ground granulated blast furnace slag (GGBS), steel slag, metakaolin and natural or artificialpozzolans such as zeolites and fly ash [18]-[22].Reduction in alkalinity (and associated pH) in thepore solution and depletion of portlandite are considered as the most beneficial effects of mineral admixtures in reducingexpansion due to alkali-silica reaction (ASR). Low Calciumfly ash would inhibit ASR at an optimumcontent in cement of 25% [15]whilst steel slag has been reported to produce up to 50% reduction in expansion [23].The effectiveness of calcined clay pozzolans such as metakaolin in suppressing alkali-silica reaction has been reported andattributed to refined pore structure which reduces ionic mobility, consumption of calcium hydroxide, and entrapmentof alkalis in silica rich hydration products [19] [24]. Granite dust is increasingly being evaluated as filler in the production of Portland cement [25] [26].

Alkali content in Portland cement is increasingly becoming higher than the stipulated safe limit of 1.0% due tothe use of early strength enhancers in current global production trends [27]. While identification of aggregate susceptibility to ASR before use [12]-[14] [28]is best practice in preventing deterioration due to ASR, most aggregates are not tested, especially in developing countries. There is therefore the need to investigate various admixtures which can beincorporated in concrete to forestall damage of structures due to ASR. This study reports effectivenessof calcined clay pozzolan, steel slag and granite dust in controlling ASR in concrete when 0% - 25% of high alkali PLC was substituted with the three mineral admixtures.

II. Materials and Methods

Low CaO steel slag for the research was obtained from Tema Steel Company Ltd, a scrap steel smelting plant in Tema – Ghana. Calcined clay pozzolan was obtained from the CSIR-BRRI Pozzolana plant located in Kumasi-Ghana, while granite dust was obtained from KAS Quarries, a granite quarry near Kumasi. Class 32.5R Portland limestone cement (PLC) manufacturedby Ghana Cement Company Limited (GHACEM) was used for the research. Pyrex glass, a known reactive aggregate [29] [30], was used for the research. Particle size of the pyrex glass ranged between 0.15 - 0.60 mm. Thechemical composition of the slag, calcined clay, granite dust and PLC were evaluated using a SpectroXlab 2000 X-Ray Fluorescencespectrophotometer.Each mineral admixture was used to replacebetween 0% and 25% of the PLC for the tests. The compositions of various mortar bar specimens are shown on Table 1.

Table 1: Mix proportions of various mortar bar samples

Mineral Admixture Content, %	Binder Content		
	Mineral Admixture, g	Mass of cement, g	Pyrex Glass, g
5	22	418	1320
10	44	396	1320
15	66	374	1320
20	88	352	1320
25	110	330	1320

ASTM C 1260 was modified for the experiment. Binder to aggregate ratio of 1:3 (instead of 1:2.25) was used in formingmortar bars of size 25 mm × 25 mm × 285 mm. Water to binder ratio of 0.5 was used instead of the specified 0.47 tocater for workability of the mortar taking into consideration the added mineral admixtures. Three mortar bars were moulded for each specimen ofmortar mix. Mortar bars were initially stored in a moist cabinet for 24 h as specified in ASTM C 1260. However,after initial length readings were taken, the specimens were further cured for 27 days in water at 20˚C to enablethe pozzolanic reaction proceed to an appreciable rate. The bars were further cured in water at 80˚C for 24 h afterwhich zero readings of the bars were measured using a length comparator recommended in ASTM C 490[31]. After taking the initial lengths, the bars were placed in 1N NaOH solution at 80˚C and subsequent length measurements were taken at 14, 21, and 35 days. The tests were replicated for combinations of slag and pozzolan – the two best performing materials in controlling ASR according to results of the initial studies on the three mineral admixtures. After 35 days, samples of some bars were treated with acetoneto stop hydration and ground for XRD analysis using a PHILLIPS PW1830 diffractometer.

III. Results and Discussion

3.1 Chemical Analysis

Chemical compositions of the materials are presented in Table 2. The Na_2O eq of all the materials exceeded 0.60%, except the calcined clay. The granite dust sample had the highest Na_2O eq of 3.84.The total oxide (SiO_2+Al_2O_3+Fe_2O_3) content of all mineral admixtures were greater than 70% while the SiO_2 content of the calcined clay and granite dust were also greater than 25% as required in ASTM C 618 [32].

Table 2: Chemical composition of calcined clay, slag, granite dust and PLC

Sample	Composition, % SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	Na_2O eq
Calcined Clay	64.50	17.20	11.40	0.60	0.15	0.48
Slag	21.31	7.50	31.52	12.44	0.26	2.36
Granite Dust	71.22	19.84	2.75	3.56	0.18	3.84
PLC	28.79	6.78	1.81	54.17	6.34	2.12

3.2Mortar Bar Expansion

Expansion of the mortar bars are shown in Figures 1 to 4. Generally expansion increased as curing age increased for all samples. The highest expansion was obtained for mortar bars prepared with granite dust. Expansion of granite dust mortar bars, shown in Figure 1, increased as granite dust content increased and reached a maximum of 25.98% at 35 days with granite dust content of 25%.The deleterious expansion of the granite dust bars could be due to the high Na_2O eq content of the dust as shown on Table 1. Referencebars (0%) also expanded rapidly as curing age increased up to a maximum of 0.35% at 35 days.

Figure 2 shows thatexpansion of mortar bars with calcined clay generally decreased as the calcined clay content increased. Optimum calcined clay content for ASR control is 25% with the lowest expansion at all test ages. As shown in Figure 3, mortar bars containing steel slag also generally increased in expansion with curing age. However higher expansions were obtained with mortar bars containing20-25% steel slag than in corresponding mortar bars made from calcined clay. Mortar bars containing 15% steel slag expanded least for the duration of test, with expansions below 0.1%. Due to the deleterious effect of granite dust on mortar bars, as indicated above, granite dust was not considered when evaluating the effect of combinations of mineral admixtures on ASR. As slag content increased in mortar bars with combined calcined clay and slag, expansion increased. However expansion of such mortar bars generally slowed after 28 days. Mortar bars containing the combination of 10% steel slag and 15% calcined clay performed best in controlling expansion.

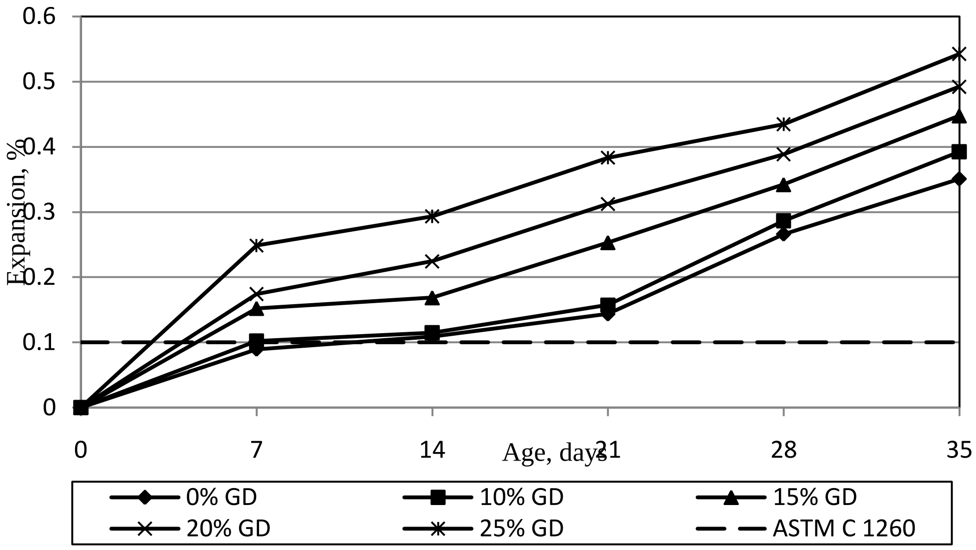


Figure 1: Expansion of granite dust mortar bars with time

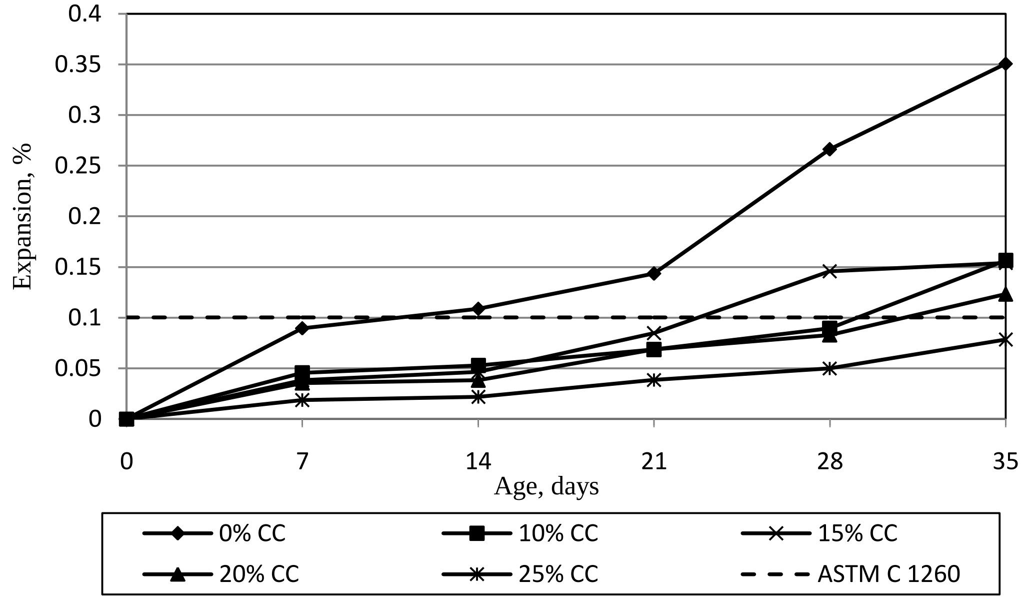


Figure 2: Expansion of calcined clay cement mortar bars with time

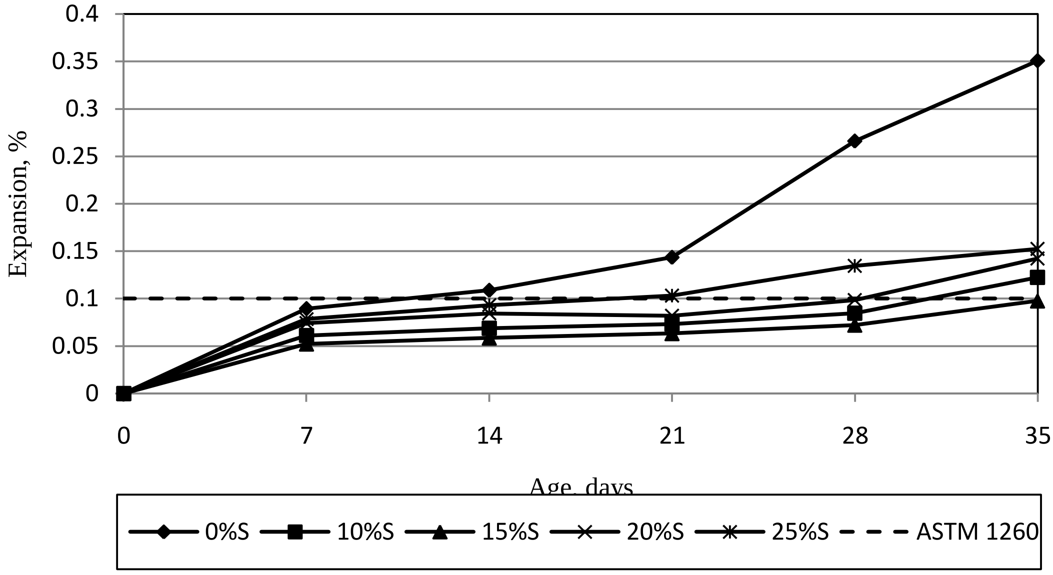


Figure 3: Expansion of steel slag mortar bars with time

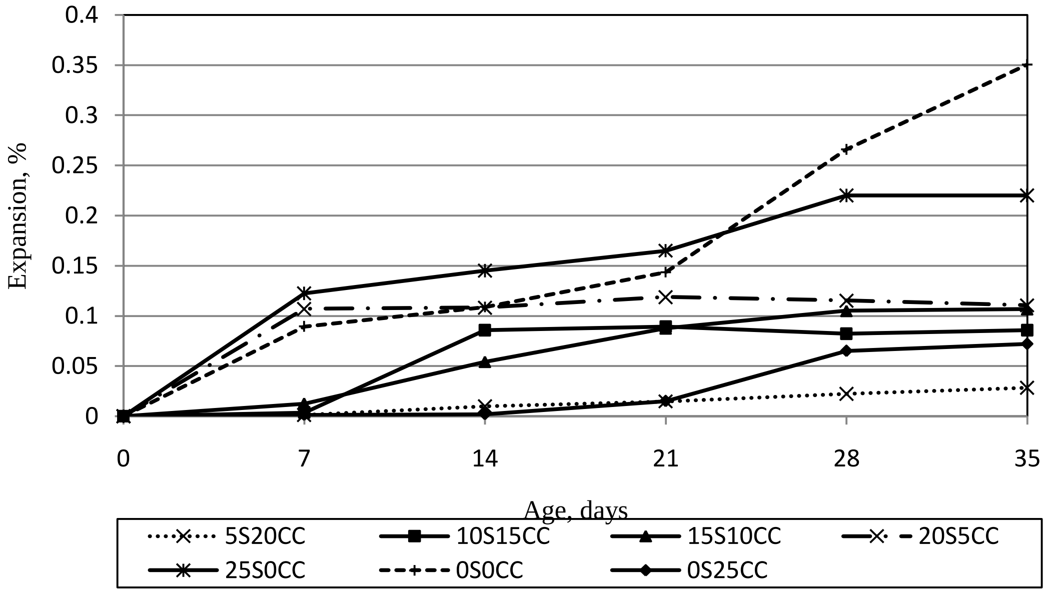


Figure 4: Expansion of calcined clay-slag mortar bars with time

3.3 Hydration Products of Mortar Bars

Figures 5-8 show XRD images of hydrated mortar bar samples at 28 days. Hydration products identified in the mortar bars after 28 days included Portlandite [$Ca(OH)_2$], Tobermorite [$Ca_5Si_6O_{16}(OH)_2$], sodium disilicate gel [$Na_2Si_2O_5$], and calcium disilicate [$CaSi_2O_5$] and Ettringite [$3CaO.Al_2O_3.3CaSO_4.32H_2O$]. Unlike the mortar bars containing calcined clay or slag, there was a high occurrence of the expansive $Na_2Si_2O_5$ in the mortar bars containing granite dust. The occurrence of higher quantities of the swelling $Na_2Si_2O_5$ is mostly contributed by the higher Na_2O eq of the granite dust cement sample as indicated in Table 2. This also explains the higher expansion of the granite dust mortar bars shown in Figure 3. $CaSi_2O_5$ formed in varyingquantities in the calcined clay and granite dust mortar bars which aided in the stabilization of the mortar matrix against expansion due to ASR.

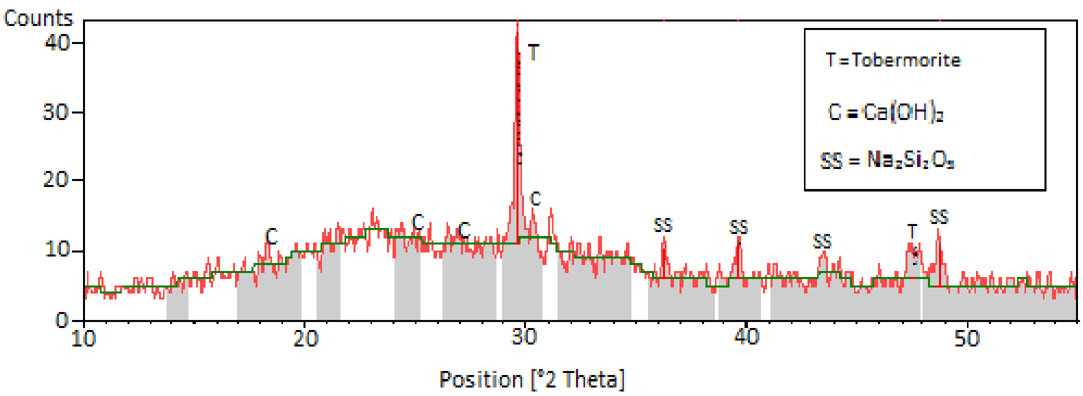


Figure 5: XRD image of 28 days old referencemortar bar sample

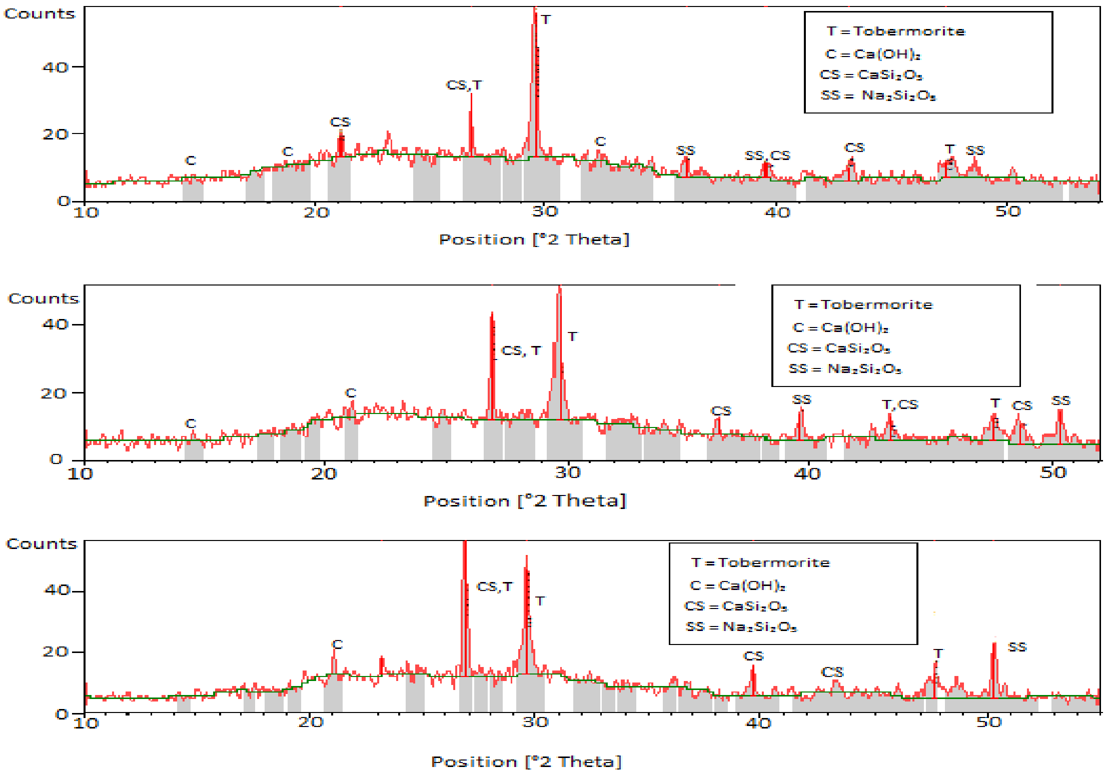
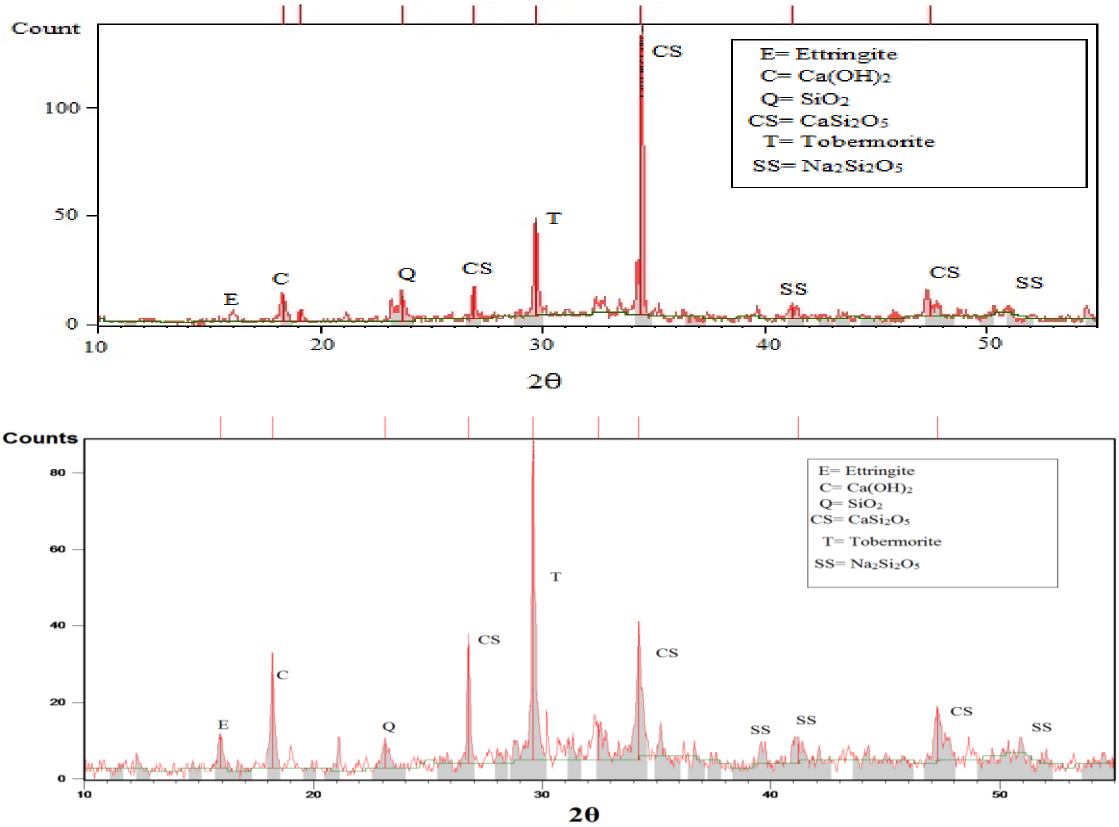


Figure 6: XRD images of mortar bars containing 5%, 15% and 25% calcined clay (top to bottom) after 28 days hydration



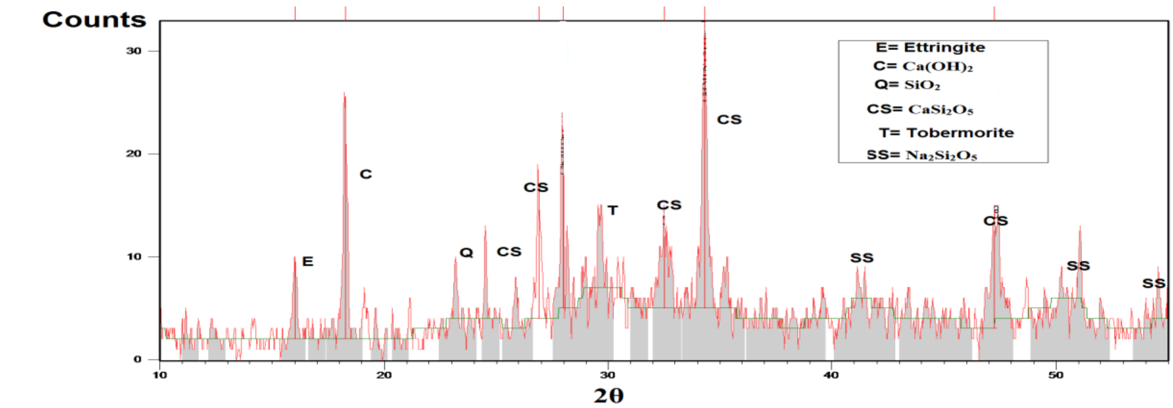


Figure 7: XRD images of mortar bar samples containing 5%, 15% and 25% granite dust (top to bottom) after 28 days hydration

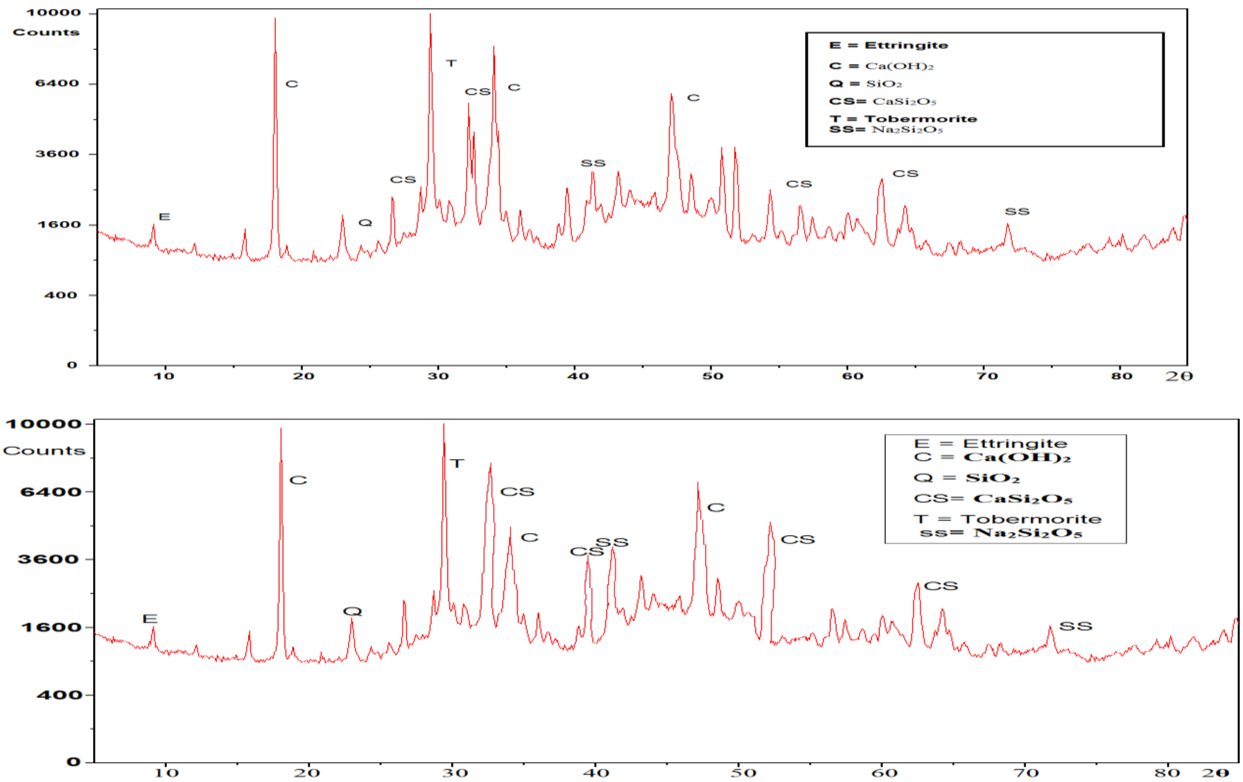


Figure 8: XRD image of mortar bars containing 5% and 25% slag (top to bottom) after 28 days hydration

IV. CONCLUSIONS AND RECOMMENDATIONS

This study has shown that alkali-silica reaction is influenced by the presence of clay pozzolan, low-CaO steel slag and granite dust. The addition of granite dust to Portland cement in quantities greater than 10% appears to have a deleterious effect on the alkali-silica reactivity of cement. Calcined clay mitigated the effect of alkali-silica reaction better than steel slag or granite dust. Optimum percentage of calcined clay needed to mitigate ASR is 25%. However, the combined effect of calcined clay and steel slag is very significant as it performs better than steel slag or calcined clay alone. The optimum combination could be 10% steel slag and 15% calcined clay. The mineralogical examination of hydrated mortar bars revealed the formation of stable $CaSi_2O_5$ in the calcined clay and steel slag mortar bars in increasing quantities as the calcined clay or steel slag content increased. The formation of $CaSi_2O_5$ is believed to be beneficial in suppressing the alkali-silica reaction.

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