



iJRASET

International Journal For Research in
Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 8

Issue: III

Month of publication: March 2020

DOI:

www.ijraset.com

Call:  08813907089

E-mail ID: ijraset@gmail.com

Mitigation of Alkali-Silica Reaction (ASR) in Concrete by using PPC - A Laboratory Investigation

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Abstract: *Aggregates containing certain constituents can react with alkali hydroxides in concrete. The reactivity is potentially harmful only when it produces significant expansion [1]. Most of the aggregates are chemically stable in hydraulic cement concrete without deleterious interaction with other concrete making materials. This alkali-aggregate reactivity (AAR) has two forms—alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). Out of two, ASR is more often a concern than ACR because the occurrence of aggregates containing reactive silica minerals is more common. The aim of the current study is to mitigate ASR by using Portland Pozzolana Cement (PPC). The outcome of the study is presented in this paper.*

Keywords: *Accelerated Mortar Bar Test (AMBT), Alkali-Aggregate Reactions (AAR), Ordinary Portland Cement (OPC); Portland Pozzolana Cement (PPC), Gel, Expansion*

I. INTRODUCTION

Alkali-aggregate reaction was first identified as a cause of concrete deterioration more than 70 years ago [2]. Since then the phenomena have been subject to a great deal of research and has been recognized as a growing problem in many areas of the world. Alkali silica reaction (ASR) is potentially a very disruptive reaction within concrete. The ASR forms a gel that swells as it extract water from the surrounding cement paste (has great affinity to moisture). By absorbing water, these gels induce pressure on the concrete matrix causing expansion resulting cracks on the micro structure of the mortar aggregate and paste composite. Presence of pore fluid in the capillary pores, alkalis and ASR reactive aggregate in concrete will initiate the process of deterioration. It is observed that reactivity is greatest for a pessimum content of reactive aggregate. The ratio of reactive alkalis to reactive silica surface area is crucial in ASR.

However, dilution of alkalis by increasing silica content by using Portland Pozzolana Cement (PPC), Portland Slag Cement (PSC), Silica Fume (SF) etc retard the rate of ASR. The objective of this study is to evaluate the mitigating effectiveness of ASR expansion while using PPC in comparison of OPC.

II. LITERATURE REVIEW

Portland cement is the main source of the alkalis. Adding fly ash (IS 1489 Part 1, 1991) induces dilution of the alkalis which disrupts ASR. Ensuring sufficient surface area by varying the percentage (BS 3892 Part1) and type of fly ash provides an efficient method to prevent ASR. Small quantities of fine fly ash with low-reactivity aggregates and sufficient alkalis may be more susceptible to ASR, if the pessimum silica alkali ratio is approached. Even when total alkalis within the concrete are as high as 5 kg/m³, fly ash has been found effective in preventing ASR (Alasali and Malhotra, 1991). The addition of fly ash reduces the pH of the pore solution to below 13 which prevents ASR. Researchers have categorized fly ash for usage for arresting ASR (Fournier and Malhotra, 1997).

It is however suggested that to restrict ASR, fly ash must comply with ASTM C618. Laboratory research [3] and field experience [4] supports that appropriate use of fly ash can prevent expansion due to ASR in concrete. Fly ash from bituminous coal sources (ASTM Class F) which is characterized by relatively low calcium contents (i.e. <10% CaO) is most effective in controlling expansion instead of those obtained from sub-bituminous or lignite coals [5–6].

The inferior performance of fly ash with calcium contents in excess of 25% may be largely ascribed to the pore solution chemistry. Such fly ash is not as effective in reducing the pore solution alkalinity of cement paste systems [7]. Greater proportion of the alkalis is available for ASR in these fly ash [8].

III. MATERIALS & METHODOLOGY

A. Materials

- 1) *Aggregates*: Coarse aggregate samples have been obtained from different quarries identified for one of the project. These coarse aggregate samples have been reduced to crushed sand sizes as mentioned in IS 383:2016 [9].
- 2) *Different Type of Cements*: Two types of cements viz. Ordinary Portland Cement (OPC) and Portland Pozzolana Cement (PPC) have been used with aggregate for studying ASR. Alkali Content and Water Cement Ratio of these cements are presented in Table 1.

Table 1: Alkali Content and Water Cement Ratio of the Cements used in the study

Type of Cement	Cement Alkalis (Na ₂ O) equivalent	Water Cement Ratio
OPC	0.62	0.45
PPC	0.88	0.45

B. Methodology

- 1) *Accelerated Mortar-Bar Test (ASTM C 1260 and ASTM C 1567) [10,11]*: The accelerated mortar-bar (AMBT) test is quick, reliable and can characterize the potential reactivity of slow as well as fast reactive aggregates. Aggregates are crushed to sand sizes for mortar-bar expansion test. The mortar bars are stored in a 1N NaOH solution to provide an immediate source of sodium and hydroxyl ions to the bars. Temperature is maintained at 80°C to accelerate the ASR. Comparator readings are taken over a period of 14 and 28 days [12, 13]. The test conditions are more severe than most field service environments. Categorized the aggregate based on 14 days expansion observation in AMBT is presented in Table 2

Table 2: Categorized the aggregate based on 14 days expansion

Average Expansion at 14 days	Reactivity
Less than or equal to 0.10%	innocuous
Greater than 0.20 %	deleteriously
Greater than 0.10% but Less than 0.20%	susceptible to reactive

- 2) *Test Conducted*: The study has been carried out using different types of cements. The details of the test and material combination used are presented in Table 3.

Table 3

Tests	Ingredient Materials
ASR	Aggregate +OPC
ASR	Aggregate +PPC

- 3) *Petrographic examination*: Petrographic examination reveals the genesis, formation and mineral compositions of the rock. On the prima facie one can assess the susceptibility of ASR reactivity looking on to their mineral composition. This assessment is only indicative and it shall be verified by performing suitable ASR tests.

Rock type; strained quartz and undulatory extinction angle of the aggregate used in study are presented below in table 4.

Table 4

Quarry	Strained quartz (%)	Undulatory extinction angle (in degree)	Name of Rock type
A	50-60	28° - 36°	quartzite
B	47-52	31°-41°	quartzite
C	45-50	31°-35°	quartzite
D	31-35	24°-26°	quartzite
E	35-40	25°-30°	quartzite

As per IS 2386 [(Part VII) : 1963] (Reaffirm Quartz) aggregate containing more than 20 percent strained quartz and undulatory extinction angle greater than 15° causing dislocation. From the mineralogical composition of the aggregate (Table 4) it reflects that the strained quartz percentage and the undulatory extinction angle exceed the critical limits. The ASR test results of aggregates with the OPC also confirm the samples falling in deleterious category.

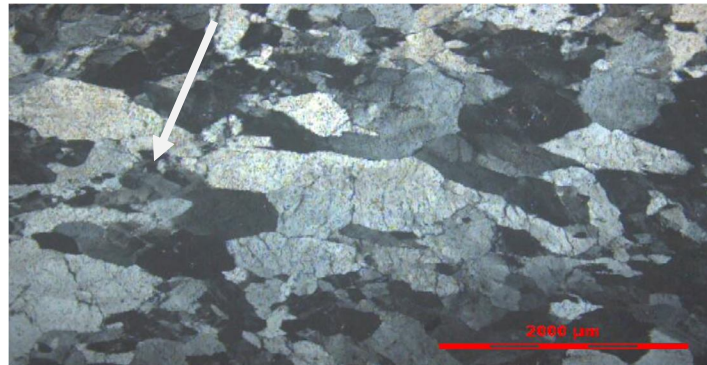


Fig. 1. Strained quartz grains in the Quartzite

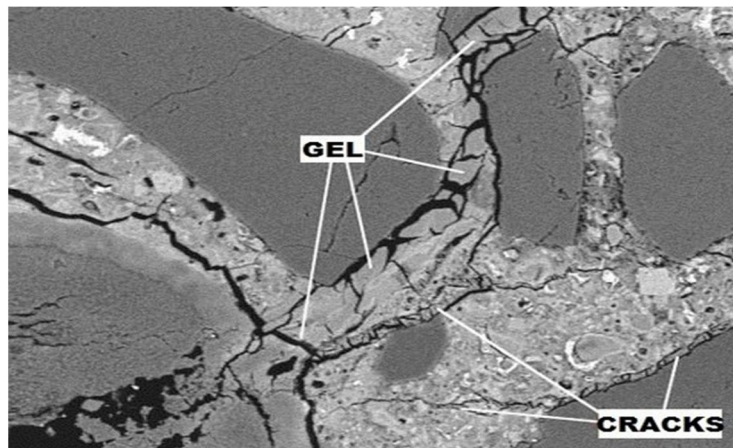
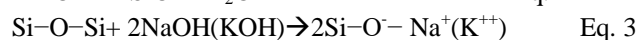
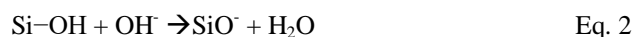
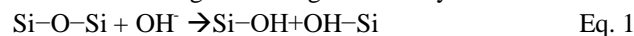


Fig 2. Alkali-silica gel extruded into cracks within the concrete

Petrographic analysis data can provide quite intrinsic information but it may mislead the whole study if sampling is not representative for the quarry. Since presence of deleterious materials cannot provide the intensity or seriousness of the deleterious reaction. Hence, field performance data is very important to assess the seriousness of the reactivity. The results of a petrographic analysis will not reveal whether an aggregate will cause deleterious expansion in concrete or not; this needs to be evaluated using other test methods.

IV. MECHANISM OF ASR

The chemical reaction of ASR is a multi-stage process [8]. The process starts with the reactive silica on the surface area of the aggregate in a high alkaline (high pH) solution. The hydroxyl ions (OH⁻) attack the stronger siloxane bridge (Si-O-Si) as it forms a poor crystallized silica network. The silanol bonds replace broken Siloxane bonds as shown in Equations 1 and 2. The positively charged alkali ions, such as Na⁺ or K⁺ balance the negative charge created by the breakdown as shown in Equation 3.



The alkali-silica reaction produces two types of component gel [11] non-swelling calcium-alkali-silicate-hydrate [C-N(K)-S-H] and swelling alkali-silica-hydrate [N(K)-S-H] gels. When the alkali-silica reaction occurs in concrete, some non-swelling C-N(K)-S-H component are produced. The presence of non-swelling gel does not coincide with distress, and thus, does not necessarily indicate destructive ASR. Only when the both types of ASR gels form the damages due to alkali-silica reactivity only occur. The occurrence of reaction products (swelling gel) is the main diagnostic symptom of ASR. [15]

The three essential components necessary for ASR-induced damage in concrete structures (as shown in figure 3) are: (1) reactive silica (from aggregates); (2) sufficient alkalis and (3) sufficient moisture. Manage with these prime factors ASR can be prevented.

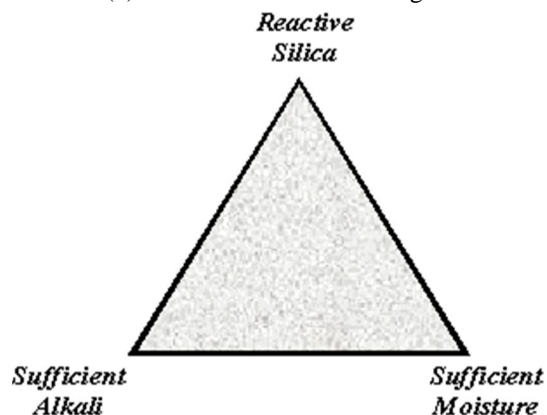


Fig:3 Three Necessary Components for ASR
(Source: FHWA [17])

A. *Reactive Silica*

The term *reactive* refers to aggregates that tend to breakdown under exposure to the highly alkaline pore solution in concrete and subsequently react with the alkali-hydroxides (sodium and potassium) to form ASR gel.

Reactive minerals are well defined and few are listed below:

- 1) Opal.
- 2) Chalcedony.
- 3) Tridymite.
- 4) Cristobalite

Cryptocrystalline, microcrystalline or glassy quartz. Coarse-grained quartz which is intensely fractured, granulated and strained internally or filled with submicroscopic inclusions of which illite is one of the most common type [16].

B. *Sufficient Alkalies*

Expansion potential is a function of the reactivity of the aggregate and of the total quantity of reactive alkalis available per cubic meter of concrete. Sources of alkalis contribution comes from cement.

C. *Sufficient Moisture*

Alkali-silica reactivity requires water to initiate the reaction. Water is an essential for the 'carrier' of alkali cations and hydroxyl ions. Water is absorbed by the gel which is the essential element in developing pressures to crack the concrete. Sufficient moisture is necessary to induce pressure on gels. These gels are formed by the alkali-silica reaction that leads to expansion and cracking of the aggregate in surrounding paste. Concrete mixtures involved in highly reactive aggregates and high-alkali cements have exposed little or no expansion in a dry environment. Likewise, the concrete structure with a large amount of local moisture typically results in more expansion [15]

V. MITIGATION STRATEGIES

In regions where occurrences of AAR are rare or the aggregate sources in use, having satisfactory field performance record verified by following the guidance in this standard, it is reasonable to continue to rely on the previous field history without subjecting the aggregates to laboratory tests for AAR [18]. AAR reactive aggregates vary from source to source. It is necessary to follow a testing programme to determine potential reactivity and to evaluate preventive methods. The level of prevention required is a function of the reactivity of the aggregate, the nature of the exposure conditions (especially availability of moisture), the criticality of the structure, and the availability of alkali in the concrete. Systematic evaluation of AAR have been shown in the figure.

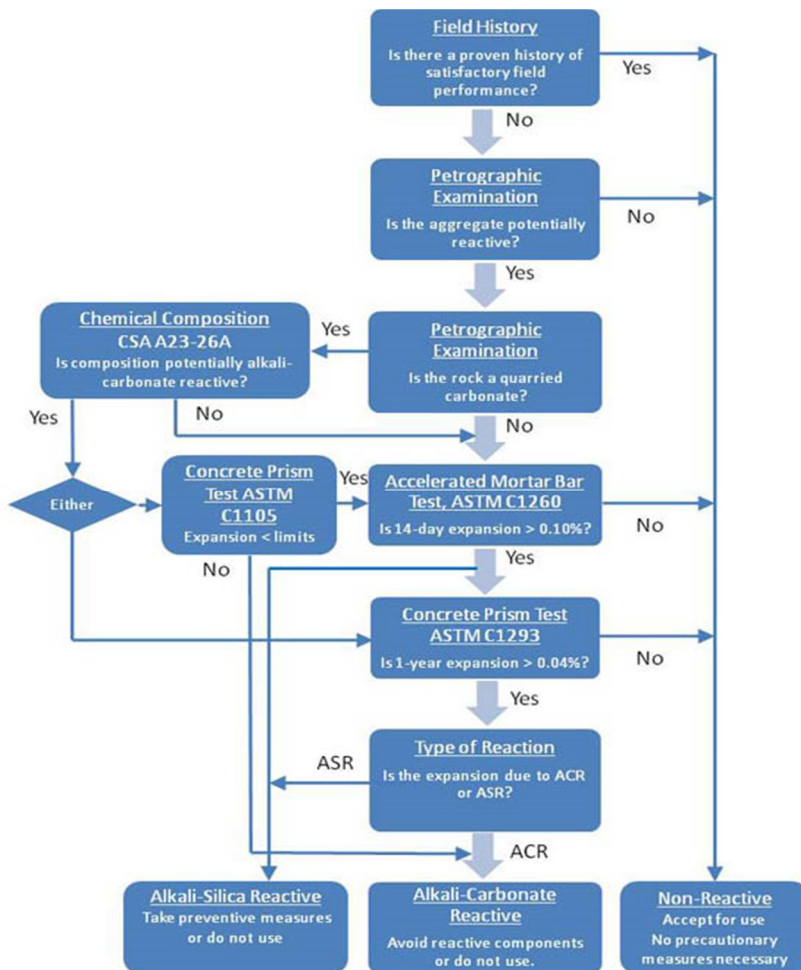


Fig. 4. Sequence of Laboratory Tests for Evaluating Aggregate Reactivity [18]

VI. RESULTS AND DISCUSSIONS

The reactivity of these aggregate with OPC and PPC have been measured by accelerated mortar bar test method (As per ASTM C 1260/ASTM C 1567). The reactivity of aggregate has been graphically presented in terms of observed expansion in figure 4 to 8. Based on 14 days expansion the cement-aggregate combination is classified in different categories of reactivity (Table 5).

Table 5

Quarry	Material Combination	% expansion after 14 days	Classification
A	Agg.+OPC	0.179	susceptible to reactive
	Agg.+PPC	0.040	innocuous
B	Agg.+OPC	0.163	susceptible to reactive
	Agg.+PPC	0.046	innocuous
C	Agg.+OPC	0.139	susceptible to reactive
	Agg.+PPC	0.029	innocuous
D	Agg.+OPC	0.145	susceptible to reactive
	Agg.+PPC	0.050	innocuous
E	Agg.+OPC	0.135	susceptible to reactive
	Agg.+PPC	0.046	innocuous

1) *Quarry A*: Comparison of mortar bar expansion with OPC and PPC at 14 days reveals that percentage expansion with OPC is susceptible to deleterious whereas with PPC expansion can be reduced by 75% as shown in the figure 5.

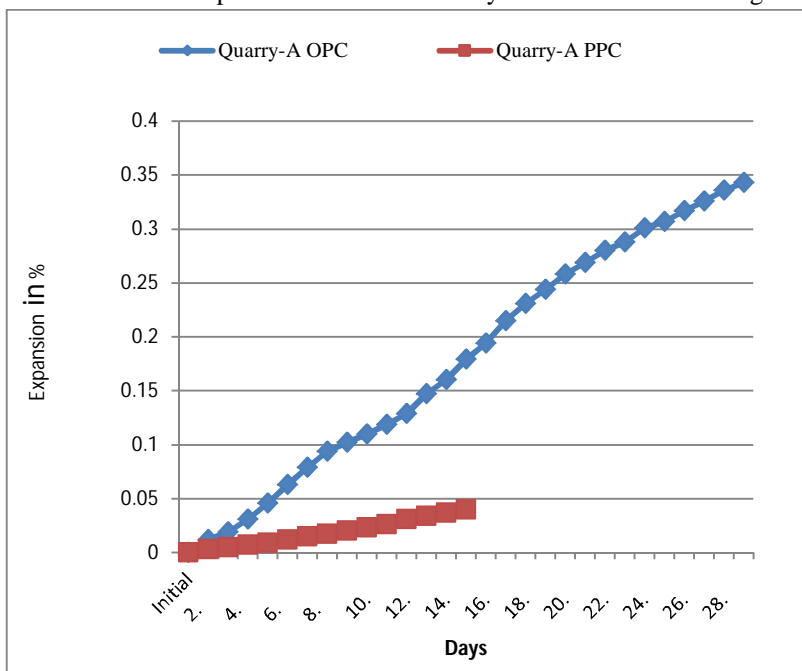


Fig: 5

2) *Quarry B*: Comparison of mortar bar expansion with OPC and PPC at 14 days reveals that percentage expansion with OPC is susceptible to deleterious whereas with PPC expansion can be reduced by 70% as shown in the figure 6.

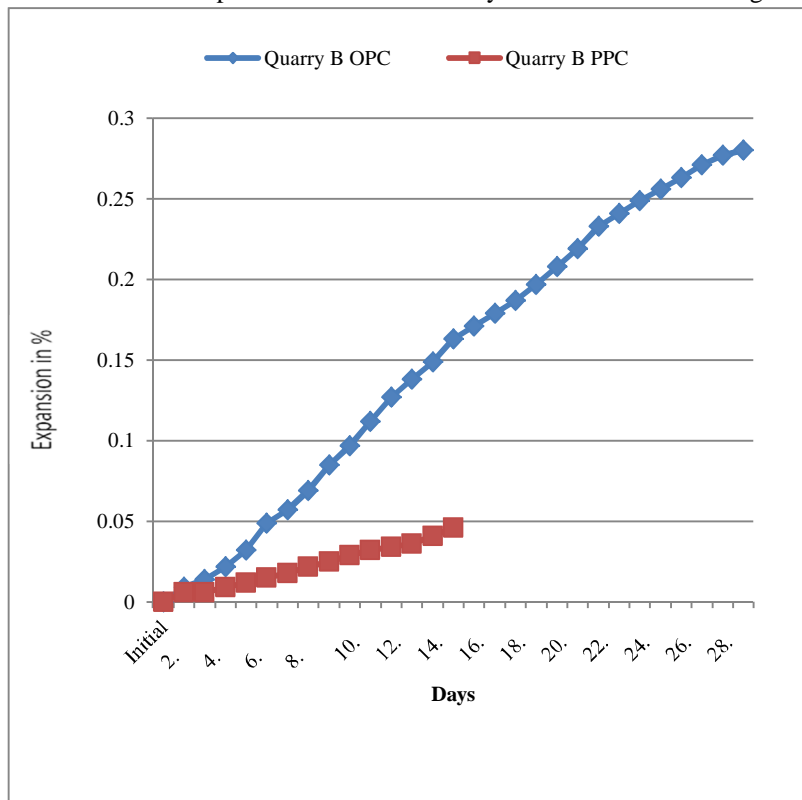


Fig: 6

3) *Quarry C*: Comparison of mortar bar expansion with OPC and PPC at 14 days reveals that percentage expansion with OPC is susceptible to deleterious whereas with PPC expansion can be reduced by 75% as shown in the figure 7.

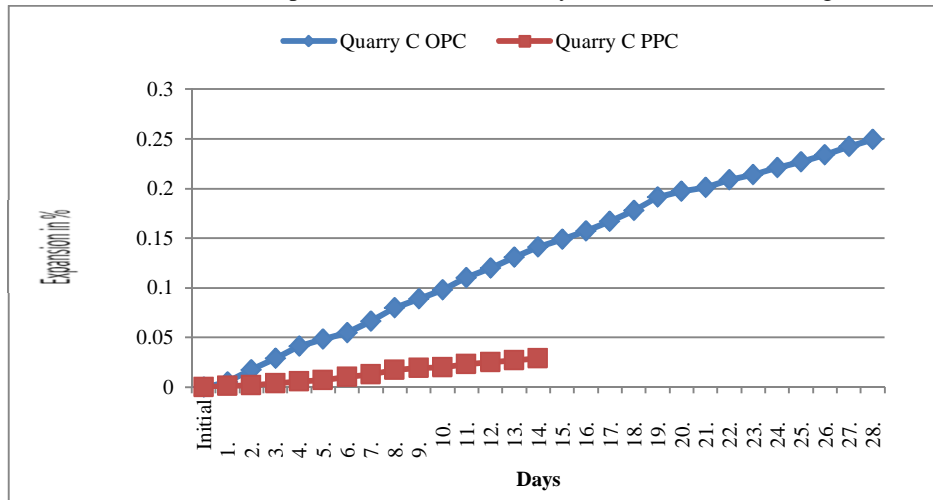


Fig: 7

4) *Quarry D*: Comparison of mortar bar expansion with OPC and PPC at 14 days reveals that percentage expansion with OPC is susceptible to deleterious whereas with PPC expansion can be reduced by 65% as shown in the figure 8.

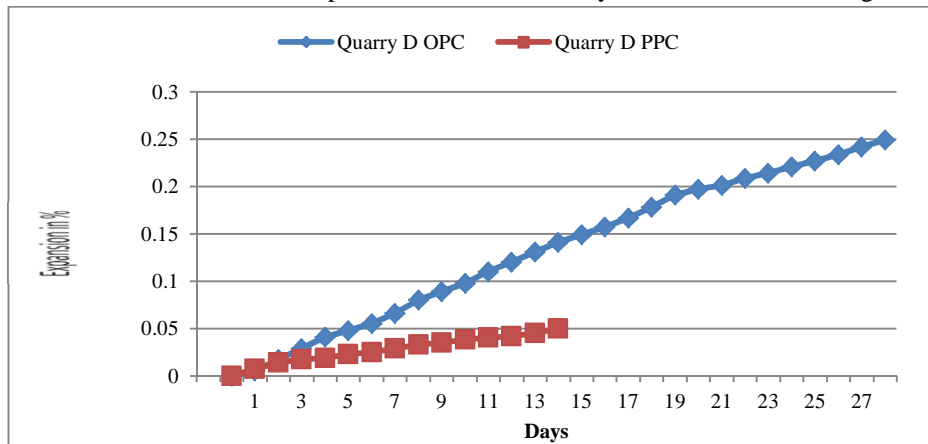


Fig: 8

5) *Quarry E*: Comparison of mortar bar expansion with OPC and PPC at 14 days reveals that percentage expansion with OPC is susceptible to deleterious whereas with PPC expansion can be reduced by 65% as shown in the figure 9.

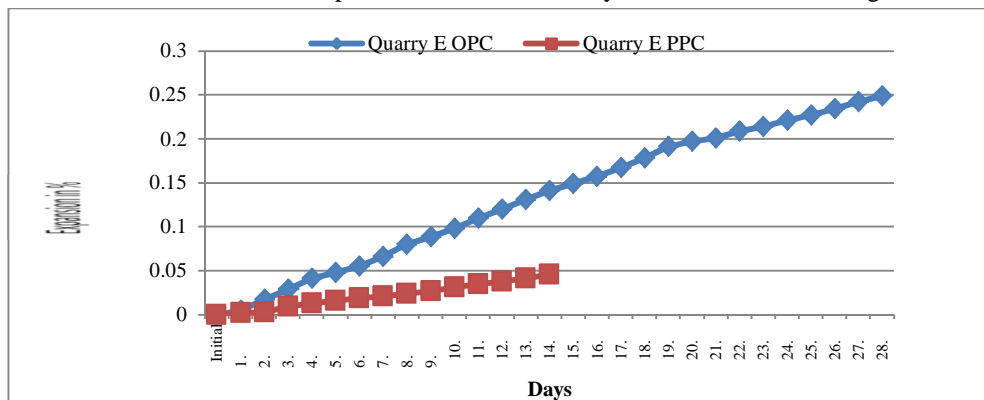


Fig: 9



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