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Hot sodium-triggered thermo-chemical degradation of concrete aggregates in the sodium resistant sacrificial layers of fast breeder reactors

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HIGHLIGHTS

- Concrete aggregates were exposed to liquid sodium exposure at 550 °C.
- Thermal and chemical effects were studied using megascopic and micro-analytical techniques.
- Aggregates underwent significant thermo-chemical degradation upon exposure.
- Limestone found more suitable for sodium environment than siliceous aggregate.

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ABSTRACT

Sodium is used as an efficient coolant in fast breeder reactor (FBR) for extracting nuclear heat from its high power density core to steam generator, to produce electricity. Accidentally spilled Sodium at elevated temperatures of 550 °C or above may interact with concrete leading to its deterioration. A sacrificial concrete layer is provided on the structural concrete to mitigate the harmful impacts of these interactions. Locally available crushed rocks like limestone and granite are employed as aggregates in sacrificial and structural concrete respectively. Rocks are naturally occurring multi-mineral and multiphase inorganic systems of the earth. Aggregates are the main constituents of concrete accounting for 70–80% of its mass. In this paper, an attempt is made to study the physico-chemical modifications that may occur in the aggregates during the interactions between liquid sodium and the aggregates of concrete. The experimental strategy consists of heating of granite, limestone and river sand aggregates at 550 °C for 30 min and further treating them with 1 Normal aqueous solution of NaOH, to differentiate thermal and chemical effects. Furthermore, sodium-aggregate interaction study at 550 °C was conducted to characterize the combined effects of heat and sodium. Siliceous aggregates (granite and river sand) were found to be easily attacked by ferric oxidation during heating in air and also subjected to rapid chemical reactions with liquid NaOH, producing mineral phases of sodium silicate, sodium orthosilicates, calcium orthosilicates and sodium carbonates. Initiation and propagation of cracking in the siliceous aggregates are sustained due to differential thermal expansion of minerals and chemical invasion of inter-granular structures. Limestone, on the other hand, was mostly stable, and its thermal performance was affected by the fraction of deleterious accessory minerals present in it. Combined action of corrosive NaOH and heat induced cracks in hot sodium environment at 550 °C may lead to more drastic degradation of concrete with siliceous aggregate than with limestone aggregate.

1. Introduction

Accidental spillage of sodium during the normal operating conditions of fast breeder reactors (FBRs) at temperatures of 550 °C and above is accompanied with interaction of hot liquid sodium with concrete. Thermal, chemical and mechanical (abrasion due to spray) effects of hot liquid sodium can bring about various deterioration mechanisms in concrete. When concrete comes in contact with hot sodium, it experiences loss of water; the released water reacts with sodium, and eventually results in formation of NaOH, sodium monoxide and gaseous hydrogen. NaOH at an elevated temperature of 550 °C and above reacts with cement and aggregate

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phases present in the concrete leading to various disintegration mechanisms (Chasanov and Staahl, 1977; Casselman, 1981; Fritzke and Schultheiss, 1983; Muhlestien and Postma, 1984; Chawla and Pederesen, 1985; Bae et al., 1998; Parida et al., 2002, 2005, 2006; Premila et al., 2008; Das et al., 2009; Haneefa et al., 2012, 2013). The maximum exposure time of hot sodium with concrete is assumed to be 30 min (Parida et al., 2006). The extent of damage is based on type, composition and age of concrete, exposure time and amount of total leaked sodium. To mitigate the consequences of hot liquid sodium on structural concrete, a sacrificial layer of special concrete is provided over it.

Concrete consists of 70% aggregate by volume; aggregates impart stability and stiffness to the concrete, and influence the performance of concrete. Additionally, the performance of concrete at elevated temperatures is primarily governed by the type of aggregate used (Savva et al., 2005; Arioz, 2007; Xing et al., 2011). Thermal and chemical degradation of different types of aggregate is governed by their distribution of particle size, mineralogy and microstructure. Granite and river sand are the commonly used aggregates for concrete in south India. Limestone is used primarily for special applications.

Sacrificial layer provided over structural members to mitigate the consequences of hot liquid sodium on concrete requires special attention in terms of thermal and chemical performance to effectively mitigate the consequences of sodium spillage accidents in FBRs. In this context, a comprehensive characterization of different types of aggregate is performed prior to their use in concrete as a sacrificial layer in FBRs. Material characterization of limestone, river sand and granite was conducted before and after thermal exposure at 550 °C for 30 min, followed by chemical exposure to NaOH. The study was supplemented with the exposure of the aggregate to an experimentally simulated hot sodium environment to understand the combined action of thermal and chemical effects.

2. Materials and methods

The principal objective of the study is to evaluate the thermo-chemical degradation of different types of aggregates in a hot sodium environment. To this purpose, the experimental programme undertaken in this study involved comprehensive characterization of limestone, granite, and river sand before and after heating in air to a temperature of 550 °C. Thermal exposure of the specimens was performed for 30 min in a muffle furnace, pre-heated to 550 °C and the heated specimens were cooled in air. Furthermore, accelerated chemical reactivity test on heated limestone, granite and river sand was carried out to study the chemical effect of 1 Normal (indicated as 1 N) aqueous solution (dissolved in water) of NaOH on aggregates at 80 °C for a test period of 14 days.

In the third stage of the study, limestone, granite and river sand were exposed to liquid sodium at 550 °C for 30 min to study the consequences of combined thermal and chemical effect of hot liquid sodium on aggregate properties. Liquid sodium exposure at 550 °C was conducted at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, India. The sodium interaction study was conducted in a carbon steel (CS) vessel of 250 mm diameter and 150 mm depth (Figs. 1 and 2) (IGCAR, 2012). The carbon steel [CS] vessel was equipped with a lid with specimen holding and handling mechanism. The aggregate samples were hung from the top lid in steel wire mesh and introduced slowly into the sodium pool; after the 30 min period of exposure, the specimens were taken out of the vessel, and cleaned with ethyl alcohol to remove residual sodium.

Micro-analytical investigations were based on optical microscopy using polarized light and thin section petrography, scanning electron microscopy (SEM) in secondary electron mode with energy dispersive X-ray analysis (EDS), thermo-gravimetric and differential thermal analysis (TG/DTA), X-ray fluorescence (XRF) and X-ray diffraction (XRD). Limestone used for the study was obtained from a crystalline limestone mine near Rajapalayam Town, Tamil Nadu, India. River sand and granite were procured from a locally available source in Chennai.

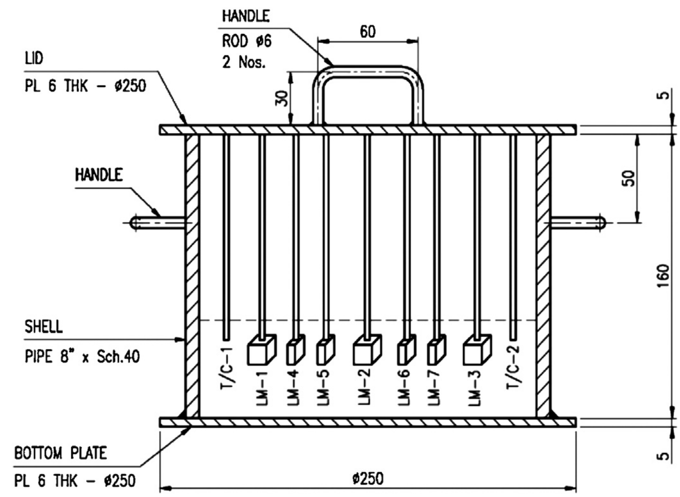

Fig. 1. Schematic of sodium exposure setup with specimens hanging from top lid.

3. Results and analysis

Results of material characterization of different types of aggregates are explained in separate sections for specimens before exposure, after heating to 550 °C, after further treatment with NaOH 1 N for a test period of 14 days, and after exposure to liquid sodium at 550 °C for 30 min.

3.1. Aggregates before exposure

Limestone used for the study exhibits three different phases as shown in Fig. 3, which include limestone with semi translucent crystals (A), massive fine-gained crystals (B) and impure

Fig. 2. Sodium exposure setup; CS vessel with thermal insulation using 150 mm glass wool associated with aluminium cladding.