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Deterioration of limestone aggregate mortars by liquid sodium in fast breeder reactor environment

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HIGHLIGHTS

- Limestone mortars were exposed to liquid sodium exposure at 550 °C.
- Micro-analytical techniques were used to characterize the exposed specimens.
- The performance of limestone mortar was greatly influenced by w/c.
- The fundamental degradation mechanisms of limestone mortars were identified.

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ABSTRACT

Hot liquid sodium at 550 °C can interact with concrete in the scenario of an accidental spillage of sodium in liquid metal cooled fast breeder reactors. To protect the structural concrete from thermo-chemical degradation, a sacrificial layer of limestone aggregate concrete is provided over it. This study investigates the fundamental mechanisms of thermo-chemical interaction between the hot liquid sodium and limestone mortars at 550 °C for a duration of 30 min in open air. The investigation involves four different types of cement with variation of water-to-cement ratios (w/c) from 0.4 to 0.6. Comprehensive analysis of experimental results reveals that the degree of damage experienced by limestone mortars displayed an upward trend with increase in w/c ratios for a given type of cement. Performance of fly ash based Portland pozzolana cement was superior to other types of cements for a w/c of 0.55. The fundamental degradation mechanisms of limestone mortars during hot liquid sodium interactions include alterations in cement paste phase, formation of sodium compounds from the interaction between solid phases of cement paste and aggregate, modifications of interfacial transition zone (ITZ), decomposition of $CaCO_3$, widening and etching of rhombohedral cleavages, and subsequent breaking through the weakest rhombohedral cleavage planes of calcite, staining, ferric oxidation in grain boundaries and disintegration of impurity minerals in limestone.

1. Introduction

Sodium is used as a coolant in the nuclear power plants based on fast breeder reactor technology. The accidental spillage of sodium at normal operating conditions of fast breeder reactors (550 °C and above) may challenge structural integrity and functional characteristics of concrete buildings (Chawla and Pederesen, 1985; Parida et al., 2006; Premila et al., 2008; Das et al., 2009; Haneefa et al., 2013a).

The thermal, chemical and mechanical (abrasion due to spray) impacts of hot liquid sodium are likely to trigger various deterioration mechanisms in the concrete structures. Leakages from the horizontal pipes may build a pool of hot liquid sodium on concrete floor and eventually lead to the most devastating exposure to sodium fires in the form of a pool or spray in the air filled building of fast reactors. The leakages from the pressurized pipes result in sodium spray fires in all the directions. However, the potential damage to concrete by sodium spray on either side of soffit of beams or slabs and lateral surface of the columns will be less than the sodium pool which is in contact with the concrete for a prolonged period. The sodium pool developed on the floor (provided with adequate slope) is assumed to be drained off to the large leak collection tanks within 30 min (Parida et al., 2006). In this

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Table 1
Chemical composition of materials.

Compositions (%)	OPC	PPC	PSC	HAC	Limestone
CaO	62.04	56.71	58.62	26.62	51.57
SiO_2	20.8	14.75	20.70	0.58	0.68
Al_2O_3	4.76	16.26	6.81	71.74	1.06
Fe_2O_3	3.96	3.94	3.28	0.12	0.32
MgO	1.88	1.22	3.17	0.27	1.67
SO_3	2.21	3.00	2.76	0.37	0.36
Loss on ignition	2.13	1.77	2.11	0.57	42.2
Total chloride (Cl)	0.01	0.01	0.03	0.01	0.02
Na_2O	0.28	0.16	0.27	0.11	–
K_2O	0.20	0.14	0.49	0.08	–
Total alkalies as Na_2O	0.41	0.22	0.52	0.16	–
TiO_2	0.19	0.22	0.23	0.06	–
Mn_2O_3	0.33	0.41	0.19	0.12	–
Sulphide (S)	–	–	0.01	–	–

Table 2
Mixes used for sodium interaction study.

Mix Cement	M1 OPC	M2 OPC	M3 OPC	M4 OPC	M5 OPC	M6 PPC	M7 PSC	M8 HAC
w/c ratio	0.40	0.45	0.50	0.55	0.60	0.55	0.55	0.55
Compressive strength (MPa) after 28 days	40.4	38.5	38.2	34.1	24.1	30.3	31.1	22.0
Flexural strength (MPa) after 28 days	7.22	5.93	5.07	4.82	3.75	5.11	3.71	4.11

context, maximum exposure duration of 30 min is considered for the sodium–concrete interaction studies. The extent of the damage depends on the type, composition, age of concrete, exposure time, amount of total sodium leaked and contact area of concrete. The thermal and chemical degradation of concrete at high temperatures and in the liquid sodium environments has been reviewed in detail by the authors (Haneefa et al., 2013a).

The concrete structures subjected to hot liquid sodium warrant special attention to ensure general and radiological safety of the nuclear reactors. In this perspective, a sacrificial layer of special concrete is laid on structural concrete to reduce the damaging impact of hot liquid sodium. Limestone is used as an aggregate in this sacrificial layer concrete, because of its superior thermo-chemical performance compared to the siliceous aggregates (Chawla and Pederesen, 1985; Parida et al., 2006; Premila et al., 2008; Das et al., 2009; Haneefa et al., 2013a, 2013b; Xing et al., 2011; Arioz, 2007; *fib* bulletin 38, 2007). The available studies on the interaction of concrete with liquid sodium are mainly focused on the engineering properties and surface disintegration. The characteristics of sodium–concrete reaction are the key factors in establishing sodium safety technology in nuclear industry. A critical analysis of all the studies carried out earlier by various investigators shows that there are major uncertainties present in quantifying the degradation characteristics of concrete reacted with hot liquid sodium. The mechanisms which govern the deterioration of concrete have to be addressed at the fundamental level. Apart from the evaluation of engineering properties; the micro-structural and mineralogical alterations in concrete need to be addressed to unravel the dynamic phenomenology associated with hot liquid sodium exposure.

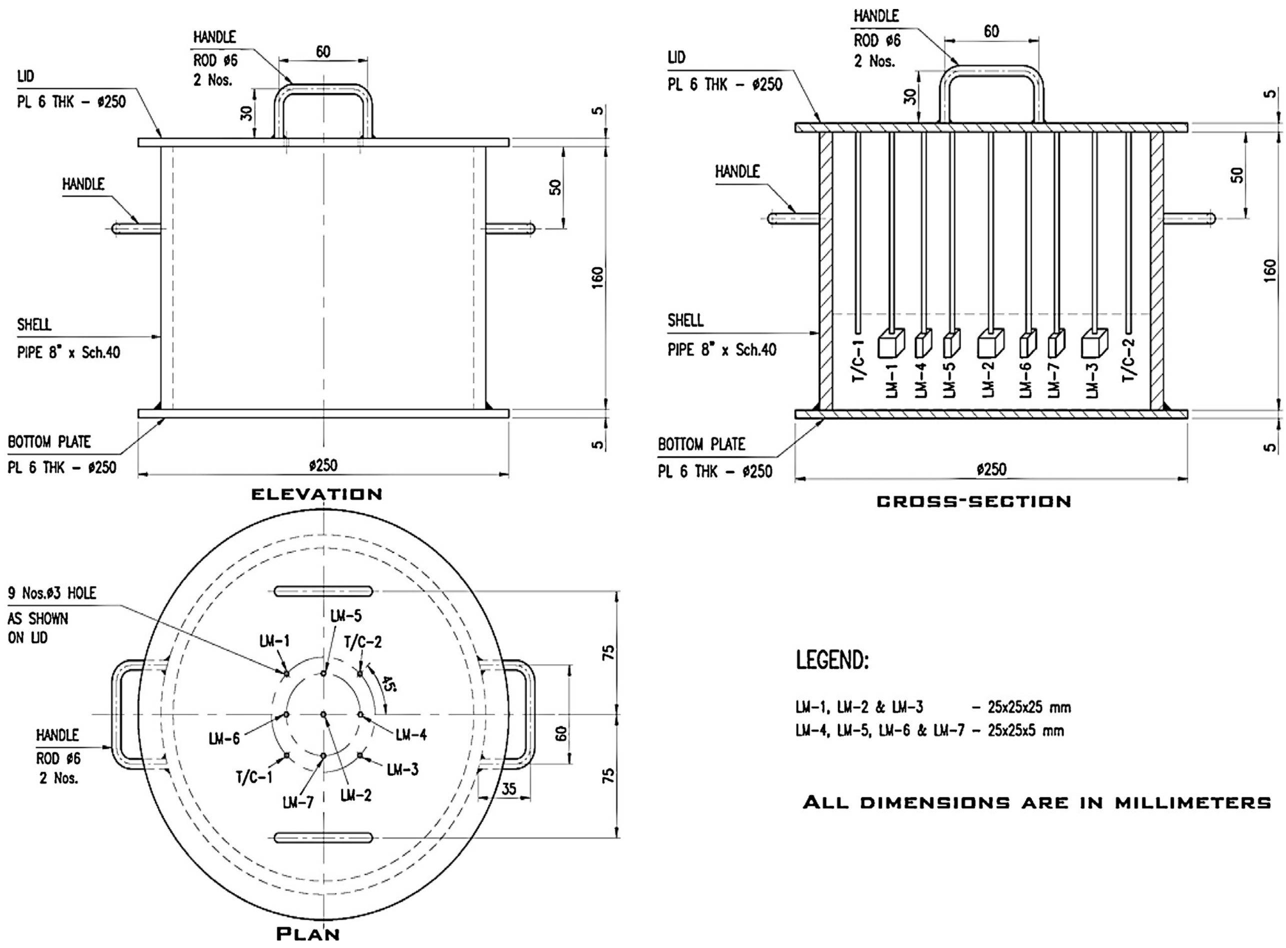

Fig. 1. Carbon steel vessel and accessory set up used for hot sodium–limestone mortar interaction study (IGCAR Report, 2012).