ANALOGS FOR LUNAR HIGHLANDS FROM SOUTHERN PENINSULAR INDIA. S. Arivazhagan[1] and S. Anbazhagan[2]

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1.0 Introduction: Any material derived from natural or synthetic, terrestrial or meteoritic components close to the mineralogy, chemical, mechanical, engineering properties and particle size distributions equivalent of a lunar or other planetary rock/ soil referred as Lunar Soil Simulant or Planetary analog [1]. The development of lunar regolith simulant is insufficient in quantity to support lunar technology projects. Samples of actual lunar regolith are limited and too small for research so that, the scientific value of the lunar soil samples is high. Hence, lunar analogs have been developed to replicate the physical, chemical, mineralogical and geotechnical properties of lunar soil for Earth based studies. Planetary scientists are using terrestrial analogs for various kinds of research and comparative studies between terrestrial and planets. The knowledge of lunar soils and its physical, chemical, mineralogical and geotechnical characteristics were obtained from various Apollo returned samples. Anorthosite, a plagioclase-rich igneous rock with subordinate amounts of pyroxenes, olivine and other minerals, is an important type of fragment found mainly in the breccias and soils at each site and as large rock fragment at the Apollo 15 site [2]. Similar rocks are available on terrestrial, which could provide vital clue about origin and evolution of the Moon. Repeated analog studies are required to understand physical, chemical and spectral properties of lunar rocks and remote mapping of the lunar surface. In southern peninsular India, there are number of anorthosite complexes available as equivalent rocks. In the present work, an emphasis has been given to the chemistry and mineralogy of southern peninsular Indian anorthosites with reference to the lunar anorthosite.

2.0 Analogs from Peninsular India: Anorthosite is a less abundant but fascinating rock composed almost entirely of calcic-plagioclase. Terrestrial anorthosite occurrences fall into a few genetic 'types' or 'associations' such as: (i) Archaean (> 2500 million years (Ma)) megacrystic, (ii) Proterozoic - massif type (2500–500 Ma) and (iii) components of layered mafic and ultramafic igneous plutons [3]& [4]. The Archean anorthosite complexes were considered as analogs to the lunar highland anorthosites. Terrestrial anorthosites grade into gabbroic anorthosites, then into anorthositic gabbros and finally into gabbros. In contrast to terrestrial anorthosites, the lunar anorthosites are much finer-crystalline and feldspars with very high Ca/Na ratios. Anorthosite samples returned from the Apollo missions contain >90% calcium-rich plagioclase [5], as well as minor amount of pyroxene and olivine, which are relatively iron-rich [6]. The plagioclase feldspars in lunar anorthosites are typically ranges from An40 to An98, although most of the rock possess An >70 [7]. Rock samples from the highlands and/ or from depths within the crust are characterized by anorthosites, norites and troctolites are collectively referred as the ANT group [8].

Layered complex of anorthositic and gabbroic rocks (SAC) are located at Sittampundi, Tamil Nadu, India. The Sm-Nd isotopic studies of Sittampundi anorthosites show an age of 2935±60 Ma, indicating the Archean age [9]. The Archean anorthosites (> 2.6 Ga) are primarily of interest because of their closer chemical similarity to highland anorthosites on the moon [10]. Oddanchatram anorthosite complex (OAC) is situated at Dindigul district, Southern region of Tamil Nadu, India and comprises of anorthosite, norite associated with charnockite, quartzite, garnet- sillimanite gneiss and magnetite-quartzite. The zircons separated from the Oddanchatram anorthosite has yielded U-Pb ages of 600Ma [11]. Kadavur anorthosite (KA) mass is a funnel shaped pluton covered about 20 km^2 area. It consists of anorthosite and gabbroic anorthosite with more mafic rocks at the boundaries grading to very coarse anorthosite in the interior. The KA complex lies south of Plaghat-Cauvery Shear Zone in the northern Madurai block (Tamil Nadu state) and crystallized at 829±14 Ma (LA –ICPMS) in a supra-subduction zone settling [12]. The mineralogical attributes (An-content of plagioclase) of the Kadavur and Oddanchatram anorthosites indicate that they represent the Proterozoic massive type anorthosite.

The Chimalpahad anorthosite Complex (CAC) is the largest, deformed and metamorphosed layered Complex in the Precambrian shield of South India [13] located at Khammam District, Andhra Pradesh. It contains a well-exposed stratigraphy of layered anorthosite-leucogabbro-gabbro-ultramafic rocks. The anorthosite body covered 200km^2 area in the Precambrian shield as irregular mass with plagioclase content of 71-86%. [14]. CAC comprised of layered gabbro anorthosite body, ultramafic rocks and massive (Alpine) type chromitite, quartzite, calc-silicate rocks, schist and gneisses. The Kondapalli layered Complex (KLC) located in the state of Andhra Pradesh, India consists of dominant gabbroic and anorthositic rocks, with subordinate ultramafic rocks. It occurs as minor bands and lenses within a region dominated by charnockites and variably deformed and cut by rare meta dolerite dykes. The KLC represents a discontinuous stratiform type complex and its disrupted fragments contain different components [15].

3.0 Chemistry and Mineralogy: The anorthositic body located in various parts of Southern peninsular India were studied and compared in terms of their equivalents with lunar highland anorthosites. The chemistry and mineralogy were considered for such correlation (Table 1 & 2). Anorthosite samples were collected from Sittampundi and Kadavur for chemical analysis. The average composition of anorthosites were compiled and listed in the Table.1. Similarly, the average chemical value of OAC, CAC and KLA were taken from published work. From the chemical values, the mineral constituents were derived using CIPW norm calculation.

4.0 Discussion: Several works have been conducted on terrestrial analogs and considered as equivalent of lunar analogs in terms of chemistry and mineralogy. Battler et al (2006) have located Archean anorthosites body in Canada, which is mineralogically similar to lunar anorthosites, featuring 90% of plagioclase with An75-95%, and 10% of pyroxene, olivine, garnet and minor amphibole. Although amphibole and garnet are not present in the lunar anorthosites, most of the terrestrial anorthosites contain small amounts of hydrated minerals, due to alteration of the pyroxene and/or olivine [23]. Anbazhagan and Arivazhagan (2010) have revealed that Sittampundi anorthosite is chemically and mineralogically equivalent of lunar anorthosite gabbro attributing 73% of plagioclase with An>67% and nearly 14-15% of pyroxene along with 5% of olivine. [19]. The analog from terrestrial may differ from genuine lunar soils in several aspects, mostly due to the effects of micrometeorites and solar wind on the moon.

Analyses of Apollo 11 samples show the anorthosites are deficient in alkalis and phosphorus due to volatilization on the surface. However, the terrestrial analogs have higher alkali contents. There is a widely accepted theory that lunar anorthosites were formed through lunar magma ocean. The anorthosites on the Earth could be the reworked and tectonically modified remnants of an original widespread early anorthositic crust on the earth formed from a global magma ocean? [24].

In the present study, chemistry of five terrestrial anorthosites form Southern peninsular India were taken along with the lunar highland geochemistry for comparison. Silicates, Al_2O_3, CaO, MgO, FeO and Fe_2O_3 are the major oxides noticed in the anorthosites. The major difference between lunar anorthosites and terrestrial analogs are absence

of five analogs, the chemistry of Sittampundi anorthosite is almost equivalent of lunar anorthosites. The other four terrestrial analogs are remain match with chemistry of lunar anorthosites, particularly with major oxides like SiO_2, Al_2O_3, CaO, MgO. Presence of minor amount of TiO_2 is noticed in all anorthosites.

Plagioclase, clino pyroxene (CPX) and ortho pyroxene (OPX) are the major mineral constituents noticed in the CIPW norm calculation. The other minor minerals are olivine, ilmenite and orthoclase. The content of CPX in lunar highland is ~3-14%, and in the terrestrial analog it fall from 0.35-14%. The CPX content of SAC and KA anorthosites matches with the LAG. The lunar highland OPX leads up to 32% whereas the terrestrial OPX is restricted to 8%. Presence of olivine noticed in LA, LAG and terrestrial anorthosites SAC, KLC. Olivine is absent in KA, OAC, and CAC. Orthoclase and quartz are represents in the LAN, KA, OAC and CAC, however those are absent in LA and LAG which is supporting the non-completion of differentiation of lunar magma. However, at present most of the research findings are supporting the presence of silicate on the lunar surface [25] & [26]. Among the five analogs, SAC found almost equivalent with lunar highland anorthosites.

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Table1. Chemistry of lunar and analog anorthosites of Souhern Peninsular India

	LA[16]	LAG[17]	LAN[18]	Terrestrial Anorthosites (Southern India)				
				SAC [19]	KA	OAC[20]	CAC[21]	KLC[22]
Type				Neo Archean (layered)	Massif	Archean	Proterozoic (layered)	Proterozoic (layered)
Age	4.46 Ga [16]			2935±60 Ma [9]	825 ± 17 Ma [12]	2600 Ma [20]	1170 Ma [21]	851±28 Ma [22]
Sio_2	45.0	48.39	45.31	44.79	49.01	54.32	51.5	48.70
TiO_2	0.5	0.9	0.36	0.085	0.71	0.046	0.044	0.16
Al_2O_3	27.2	20.68	20.44	25.69	21.14	28.26	27.15	28.12
Fe_2O_3	-	-	-	3.27	8.54	0.646	1.63	0.86
FeO	5.2	8.85	12.60	-	-	-	-	2.94
MgO	5.7	7.79	6.88	5.78	4.29	0.296	1.439	3.12
CaO	15.7	12.13	14.41	16.52	12.34	11.22	14.89	13.74
Na_2O	-	0.02	0.15	1.37	3.11	4.506	1.729	2.37
K_2O	-	0.01	0.01	0.06	0.53	0.692	0.023	-
P_2O_5	-	0.02	-	0.02	0.01	0.032	0.045	0.03
Total	99.3	98.79	100.16	97.58	99.84	100.90	98.45	100.04

LA- Lunar Anorthosite; LAG-Lunar Anorthositic Gabbro; LGA-Lunar Gabbroic Anorthosite; SAC-Sittampundi; KA-Kadavur; OAC-Oddanchatram; CAC-Chimalpahad; KLC-Kondapalli

Table.2: Mineralogical constitutes of lunar anorthosites and terrestrial analog of Southern peninsular India

Minerals	LA	LAG	LAN	SAC	KA	OAC	CAC	KLC
Quartz	-	-	4.74	-	0.184	1.2	9.01	-
Orthoclase	-	0.059	0.059	0.355	3.132	4.09	0.136	-
Plagioclase	74.21	56.32	56.46	73.13	70.66	92.96	80.88	86.13
Clino pyroxene	2.99	13.71	3.17	13.83	12.86	0.35	5.67	1.52
Ortho pyroxene	20.28	19.45	32.61	-	4.72	0.57	0.95	8.87
Olivine	0.85	9.91	-	5.59	-	-	-	1.87
Magnetite	-	-	-	-	-	-	-	1.24
Ilmenite	0.95	0.68	1.71	-	-	-	0.06	0.3
Hematite	-	-	-	3.27	8.54	0.64	1.63	-
Total	99.28	100.12	98.74	96.17	100.09	99.81	98.33	99.93