Research Article

A Comprehensive Study on Gamma-Ray Exposure Build-Up Factors and Fast Neutron Removal Cross Sections of Fly-Ash Bricks

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Geometric progression (GP) method was utilized to investigate gamma-ray exposure build-up factors of fly-ash bricks for energies from 0.015 to 15 MeV up to 40 mfp penetration depth. The EBFs of the fly-ash bricks are dependent upon the photon energy, penetration depths, and the chemical compositions of the elements. Appreciable variations in exposure build-up factor (EBF) are noted for the fly-ash bricks. The EBFs were found to be small in low and high photon energy regions whereas very large in medium energy region. EBF of the bricks is inversely proportional to equivalent atomic number below 10 mfp for entire energy region of interest 0.015 to 15 MeV. The EBFs of fly-ash, brick of mud, and common brick were similar at 1.5 MeV photon energy. The EBF of the fly-ash bricks was found to be higher than that of the brick of mud, and common brick. The fast neutron removal cross sections of the fly-ash bricks, brick of mud, and common bricks were also calculated which were found to be in the same order. It is expected that this study should be very directly useful for shielding effectiveness of fly-ash brick materials and dose estimation.

1. Introduction

Safety inside residential and nonresidential building against the radiation is evaluated by the shielding properties by the parameters such as mass attenuation coefficients, energy absorption coefficients, and half-value layer. Gamma-ray interacts with material by photoelectric absorption, Compton scattering, and pair production, which depends upon photon energy and element compositions. The intensity of a gamma-ray beam through a medium follows the Lambert Beer law under three conditions namely, (i) monochromatic rays, (ii) thin absorbing material, and (iii) narrow beam geometry. In case, any of the above conditions is not being met, this law is no longer applicable. The law can be applicable by using a correction factor, called as “build-up factor.”

The concept of build-up factor was introduced in late 1950 [2] by obtaining experimentally the build-up factor at 1.25 MeV gamma-ray energy for water up to 16 mfp. The importance of build-up factor in attenuation studies was further recognized for multienergy gamma-rays with poor

geometry [3]. Since 1950, due to the availability of reasonably accurate values of attenuation coefficients and cross section of the various mediums, a great progress has been made in the computation of build-up factor in different types of materials such as medical, dosimetric, shielding, and radiation protection.

The build-up factor is a dimensionless multiplication factor which corrects the response of uncollided photon beam. The build-up is defined as the ratio of total value of specified radiation quantity at any point to the contribution to that value from radiation reaching the point without having undergone a collision. There are two types of build-up factors which are the quantity of interest: (a) the absorbed or deposited energy in the interacting materials and detector response function is that of absorption in the interacting medium; (b) the exposure build-up factor in which quantity of interest is the exposure and detector response function is that of absorption in air [4]. The build-up factors have been computed by various codes such as PALLAS [5], ADJMON-I [6, 7], ASFIT [8], and EGS4 [9]. These codes are using

TABLE 1: Elemental compositions of fly-ash bricks, brick of mud, and common brick [1].

Element	Elemental composition (% by weight)									
Density (g cm^{-3})	FAB1	FAB2	FAB3	FAB4	FAB5	FAB6	FAB7	FAB8	BOM	COM
	1.87	1.81	1.76	1.72	1.85	1.79	1.74	1.70	1.82	1.87
H	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	—	0.24
C	3.69	3.41	3.13	2.84	1.70	1.70	1.70	1.70	—	0.06
N	—	—	—	—	—	—	—	—	—	0.01
O	48.71	48.70	48.69	48.68	49.96	49.77	49.58	49.39	54.6	45.35
Na	0.01	0.01	0.01	0.01	0.11	0.09	0.08	0.07	0.11	0.01
Mg	1.07	1.03	0.99	0.94	0.77	0.77	0.77	0.77	0.11	0.04
Al	11.77	11.13	10.5	9.86	10.78	10.28	9.79	9.29	4.95	7.88
Si	23.22	23.09	22.96	22.83	25.08	24.68	24.29	23.9	5.96	20.78
P	—	—	—	—	0.07	0.06	0.05	0.04	—	—
S	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.02	—	0.02
K	0.42	0.80	1.18	1.56	0.44	0.82	1.20	1.57	—	2.66
Ca	6.92	6.77	6.61	6.45	7.32	7.10	6.88	6.67	34.01	4.75
Ti	0.01	0.01	0.01	0.01	0.57	0.49	0.41	0.33	—	0.09
Mn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	—	0.17
Fe	4.07	4.95	5.84	6.73	3.12	4.15	5.17	6.19	0.30	17.96

TABLE 2: Equivalent atomic number of fly-ash bricks and other bricks.

Energy (MeV)	Equivalent atomic number (Z_{eq})									
	FAB1	FAB2	FAB3	FAB4	FAB5	FAB6	FAB7	FAB8	BOM	COB
0.015	13.16	13.39	13.61	13.81	13.12	13.35	13.58	13.79	14.61	15.97
0.02	13.32	13.56	13.78	14.00	13.27	13.51	13.75	13.97	14.78	16.22
0.03	13.50	13.74	13.98	14.20	13.43	13.69	13.93	14.16	14.95	16.50
0.04	13.61	13.87	14.11	14.34	13.53	13.80	14.06	14.30	15.06	16.67
0.05	13.69	13.95	14.20	14.44	13.62	13.89	14.15	14.40	15.14	16.79
0.06	13.76	14.03	14.27	14.51	13.69	13.96	14.21	14.47	15.20	16.88
0.08	13.85	14.13	14.37	14.61	13.77	14.04	14.31	14.56	15.28	17.02
0.1	13.91	14.21	14.43	14.68	13.83	14.10	14.37	14.63	15.33	17.12
0.15	14.02	14.33	14.54	14.80	13.91	14.19	14.47	14.74	15.41	17.24
0.2	14.07	14.33	14.60	14.87	13.96	14.25	14.53	14.81	15.46	17.31
0.3	14.13	14.40	14.67	14.95	14.02	14.31	14.60	14.89	15.51	17.40
0.4	14.16	14.44	14.72	15.00	14.05	14.34	14.64	14.93	15.54	17.45
0.5	14.18	14.46	14.74	15.02	14.07	14.36	14.66	14.96	15.55	17.48
0.6	14.19	14.47	14.76	15.04	14.08	14.38	14.67	14.97	15.56	17.50
0.8	14.20	14.48	14.77	15.05	14.08	14.39	14.68	14.98	15.57	17.52
1	14.20	14.49	14.77	15.05	14.09	14.39	14.69	14.99	15.57	17.52
1.5	12.22	12.44	12.65	12.86	12.23	12.44	12.66	12.87	13.66	15.15
2	11.69	11.85	12.01	12.16	11.74	11.89	12.04	12.19	13.00	14.01
3	11.56	11.71	11.85	11.99	11.62	11.75	11.89	12.02	12.82	13.70
4	11.52	11.66	11.80	11.94	11.57	11.71	11.84	11.97	12.76	13.63
5	11.51	11.64	11.78	11.92	11.56	11.70	11.83	11.96	12.75	13.59
6	11.50	11.63	11.77	11.91	11.56	11.69	11.81	11.94	12.73	13.57
8	11.49	11.62	11.76	11.90	11.54	11.67	11.80	11.93	12.72	13.54
10	11.48	11.61	11.75	11.89	11.54	11.67	11.79	11.92	12.71	13.53
15	11.47	11.61	11.74	11.88	11.53	11.66	11.79	11.91	12.70	13.51

an accurate algorithmic for the Klein-Nishina cross section which eliminated other sources of errors.

The compilation for build-up factors by various codes was reported in ANSI/ANS-6.4.3-1991 by American Nuclear Society [10]. The data in the report covers energy range from 0.015 to 15 MeV up to penetration depth of 40 mean free path (mfp). The build-up factors in the ANS-6.4.3 are for 23

elements of atomic number, $Z = 4$ to 92. The build-up factors of ANS-6.4.3 can be calculated by invariant embedding [11, 12]. Harima et al. [13] developed a fitting formula, called geometric progression (GP), which gave build-up factors of the good agreement with the ANS-6.4.3. The GP fitting is more accurate than three exponential fit in the water medium. The GP fitting formula is known to be accurate within the

TABLE 3: GP fitting parameters for FAB1 and FAB2.

Energy (MeV)	b	c	a	X_K	d
FAB1					
0.015	1.028	0.386	0.215	14.919	-0.146
0.02	1.062	0.398	0.206	15.078	-0.116
0.03	1.201	0.408	0.207	14.534	-0.110
0.04	1.421	0.476	0.180	14.500	-0.100
0.05	1.677	0.605	0.124	15.483	-0.065
0.06	1.963	0.701	0.095	14.727	-0.053
0.08	2.435	0.851	0.055	14.413	-0.048
0.1	2.646	1.026	0.014	13.593	-0.029
0.15	2.731	1.272	-0.042	10.413	-0.006
0.2	2.670	1.371	-0.057	7.813	-0.005
0.3	2.476	1.464	-0.077	17.191	0.013
0.4	2.350	1.467	-0.080	16.046	0.016
0.5	2.247	1.451	-0.079	16.302	0.018
0.6	2.171	1.422	-0.076	18.225	0.021
0.8	2.049	1.383	-0.073	15.355	0.021
1	1.976	1.323	-0.063	16.064	0.019
1.5	1.864	1.232	-0.048	14.866	0.017
2	1.789	1.155	-0.033	15.608	0.011
3	1.678	1.061	-0.012	13.922	-0.001
4	1.602	0.995	0.005	12.945	-0.009
5	1.537	0.948	0.020	12.601	-0.021
6	1.474	0.924	0.027	11.700	-0.022
8	1.406	0.902	0.033	13.689	-0.027
10	1.345	0.881	0.042	13.141	-0.033
15	1.258	0.835	0.061	14.297	-0.052
FAB2					
0.015	1.027	0.376	0.228	14.103	-0.155
0.02	1.058	0.408	0.197	15.983	-0.113
0.03	1.190	0.402	0.212	14.267	-0.113
0.04	1.397	0.466	0.185	14.389	-0.104
0.05	1.646	0.583	0.133	15.174	-0.071
0.06	1.890	0.700	0.093	15.276	-0.052
0.08	2.374	0.827	0.061	14.429	-0.051
0.1	2.586	1.001	0.016	13.739	-0.032
0.15	2.692	1.248	-0.037	10.823	-0.009
0.2	2.647	1.356	-0.055	8.168	-0.006
0.3	2.462	1.454	-0.076	17.822	0.013
0.4	2.342	1.458	-0.078	16.424	0.015
0.5	2.239	1.445	-0.078	16.305	0.017
0.6	2.162	1.420	-0.076	17.592	0.020
0.8	2.044	1.380	-0.072	15.458	0.021
1	1.970	1.323	-0.063	16.408	0.019
1.5	1.862	1.232	-0.048	15.186	0.017
2	1.788	1.155	-0.033	15.865	0.011
3	1.677	1.062	-0.012	14.771	-0.001
4	1.601	0.995	0.005	12.967	-0.009
5	1.537	0.946	0.021	11.908	-0.021
6	1.477	0.927	0.026	11.786	-0.021
8	1.405	0.902	0.034	13.732	-0.028
10	1.344	0.882	0.042	13.128	-0.033
15	1.257	0.838	0.060	14.282	-0.052

TABLE 4: GP fitting parameters for FAB3 and FAB4.

Energy (MeV)	b	c	a	X_K	d
FAB3					
0.015	1.025	0.366	0.240	13.337	-0.164
0.02	1.054	0.417	0.188	16.831	-0.110
0.03	1.180	0.396	0.216	14.016	-0.116
0.04	1.377	0.458	0.189	14.341	-0.108
0.05	1.618	0.567	0.141	15.031	-0.086
0.06	1.854	0.683	0.099	15.149	-0.055
0.08	2.327	0.808	0.068	14.016	-0.051
0.1	2.542	0.984	0.020	13.835	-0.034
0.15	2.667	1.232	-0.034	11.093	-0.010
0.2	2.624	1.341	-0.052	8.518	-0.007
0.3	2.448	1.444	-0.074	18.446	0.013
0.4	2.333	1.449	-0.077	16.798	0.015
0.5	2.231	1.439	-0.077	16.307	0.016
0.6	2.154	1.418	-0.075	16.966	0.019
0.8	2.039	1.377	-0.071	15.559	0.021
1	1.964	1.323	-0.063	16.748	0.020
1.5	1.859	1.231	-0.048	15.503	0.017
2	1.787	1.155	-0.033	16.105	0.011
3	1.675	1.063	-0.013	15.611	-0.002
4	1.600	0.996	0.005	12.989	-0.009
5	1.538	0.944	0.022	11.222	-0.021
6	1.480	0.930	0.026	11.870	-0.020
8	1.405	0.902	0.034	13.775	-0.028
10	1.343	0.884	0.041	13.114	-0.033
15	1.255	0.841	0.059	14.267	-0.052
FAB4					
0.015	1.024	0.357	0.252	12.616	-0.172
0.02	1.051	0.426	0.179	17.628	-0.108
0.03	1.171	0.395	0.215	14.076	-0.033
0.04	1.360	0.453	0.190	14.365	-0.107
0.05	1.592	0.553	0.147	14.928	-0.080
0.06	1.820	0.666	0.105	15.025	-0.058
0.08	2.278	0.788	0.074	13.592	-0.051
0.1	2.494	0.964	0.025	13.941	-0.037
0.15	2.635	1.213	-0.030	11.426	-0.012
0.2	2.601	1.326	-0.049	8.863	-0.008
0.3	2.434	1.435	-0.072	19.060	0.013
0.4	2.325	1.440	-0.075	17.165	0.014
0.5	2.223	1.433	-0.076	16.309	0.016
0.6	2.146	1.415	-0.075	16.510	0.018
0.8	2.035	1.374	-0.071	15.691	0.020
1	1.959	1.322	-0.063	16.955	0.020
1.5	1.857	1.230	-0.048	15.815	0.017
2	1.786	1.155	-0.033	15.976	0.011
3	1.674	1.064	-0.013	16.447	-0.002
4	1.598	0.997	0.005	13.010	-0.009
5	1.538	0.942	0.023	10.541	-0.022
6	1.482	0.932	0.025	11.955	-0.020
8	1.405	0.902	0.034	13.818	-0.028
10	1.343	0.885	0.041	13.101	-0.033
15	1.254	0.844	0.058	14.253	-0.051

estimated uncertainty (<5%) and Harima [4] had extensive historical review and reported the current gamma photon

build-up factors and applications [14]. Various researchers have investigated gamma-ray build-up factors in different

TABLE 5: GP fitting parameters for FAB5 and FAB6.

Energy (MeV)	b	c	a	X_K	d
FAB5					
0.015	1.028	0.389	0.213	15.089	-0.144
0.02	1.062	0.395	0.209	14.855	-0.117
0.03	1.204	0.410	0.206	14.612	-0.110
0.04	1.429	0.480	0.178	14.539	-0.099
0.05	1.687	0.611	0.122	15.574	-0.063
0.06	1.984	0.700	0.096	14.558	-0.056
0.08	2.453	0.857	0.053	14.293	-0.038
0.1	2.663	1.033	0.009	13.540	-0.021
0.15	2.745	1.280	-0.043	11.334	0.006
0.2	2.679	1.378	-0.059	8.048	0.011
0.3	2.482	1.468	-0.078	16.930	0.014
0.4	2.354	1.471	-0.081	15.887	0.016
0.5	2.250	1.454	-0.080	16.301	0.018
0.6	2.175	1.423	-0.076	18.496	0.021
0.8	2.051	1.384	-0.073	15.311	0.021
1	1.978	1.323	-0.063	15.916	0.019
1.5	1.864	1.232	-0.048	14.873	0.017
2	1.789	1.155	-0.033	15.683	0.011
3	1.678	1.061	-0.012	14.248	-0.001
4	1.601	0.995	0.005	12.954	-0.009
5	1.537	0.947	0.021	12.308	-0.021
6	1.475	0.925	0.027	11.737	-0.022
8	1.405	0.902	0.034	13.708	-0.027
10	1.344	0.881	0.042	13.135	-0.033
15	1.258	0.836	0.060	14.290	-0.052
FAB6					
0.015	1.027	0.378	0.226	14.230	-0.153
0.02	1.058	0.406	0.199	15.816	-0.114
0.03	1.192	0.403	0.211	14.326	-0.113
0.04	1.403	0.468	0.184	14.417	-0.103
0.05	1.653	0.588	0.131	15.251	-0.069
0.06	1.907	0.702	0.093	15.187	-0.052
0.08	2.391	0.834	0.059	14.583	-0.051
0.1	2.607	1.010	0.014	13.694	-0.031
0.15	2.709	1.258	-0.039	10.645	-0.008
0.2	2.654	1.361	-0.055	8.052	-0.006
0.3	2.467	1.458	-0.076	17.611	0.013
0.4	2.344	1.461	-0.079	16.295	0.015
0.5	2.242	1.447	-0.079	16.304	0.017
0.6	2.165	1.421	-0.076	17.812	0.020
0.8	2.046	1.381	-0.072	15.422	0.021
1	1.972	1.323	-0.063	16.288	0.019
1.5	1.862	1.232	-0.048	15.195	0.017
2	1.788	1.155	-0.033	15.931	0.011
3	1.676	1.062	-0.013	15.053	-0.001
4	1.600	0.996	0.005	12.975	-0.009
5	1.537	0.945	0.022	11.655	-0.021
6	1.478	0.928	0.026	11.817	-0.021
8	1.405	0.902	0.034	13.749	-0.028
10	1.344	0.883	0.042	13.122	-0.033
15	1.256	0.839	0.059	14.276	-0.052

TABLE 6: GP fitting parameters for FAB7 and FAB8.

Energy (MeV)	b	c	a	X_K	d
FAB7					
0.015	1.025	0.368	0.239	13.437	-0.162
0.02	1.055	0.416	0.189	16.700	-0.111
0.03	1.182	0.397	0.215	14.062	-0.116
0.04	1.381	0.459	0.188	14.336	-0.107
0.05	1.624	0.570	0.139	15.055	-0.074
0.06	1.863	0.687	0.098	15.178	-0.054
0.08	2.339	0.813	0.066	14.122	-0.051
0.1	2.554	0.989	0.019	13.808	-0.038
0.15	2.675	1.237	-0.035	11.003	-0.010
0.2	2.630	1.345	-0.053	8.423	-0.007
0.3	2.452	1.447	-0.074	18.271	0.013
0.4	2.336	1.452	-0.077	16.691	0.015
0.5	2.233	1.440	-0.077	16.307	0.017
0.6	2.157	1.419	-0.075	17.148	0.019
0.8	2.041	1.378	-0.072	15.529	0.021
1	1.965	1.323	-0.063	16.649	0.020
1.5	1.859	1.231	-0.048	15.509	0.017
2	1.787	1.155	-0.033	16.068	0.011
3	1.675	1.063	-0.013	15.844	-0.002
4	1.599	0.996	0.005	12.995	-0.009
5	1.538	0.944	0.023	11.014	-0.021
6	1.480	0.930	0.025	11.897	-0.020
8	1.405	0.902	0.034	13.789	-0.028
10	1.343	0.884	0.041	13.110	-0.033
15	1.255	0.842	0.058	14.263	-0.052
FAB8					
0.015	1.024	0.358	0.251	12.694	-0.171
0.02	1.051	0.425	0.180	17.526	-0.108
0.03	1.173	0.395	0.215	14.061	-0.116
0.04	1.363	0.453	0.190	14.361	-0.107
0.05	1.597	0.555	0.146	14.946	-0.079
0.06	1.826	0.669	0.104	15.048	-0.057
0.08	2.071	0.792	0.073	13.676	-0.051
0.1	2.422	0.968	0.024	13.919	-0.036
0.15	2.642	1.217	-0.031	11.354	-0.012
0.2	2.606	1.329	-0.050	8.786	-0.008
0.3	2.437	1.437	-0.073	18.919	0.013
0.4	2.327	1.442	-0.075	17.080	0.014
0.5	2.225	1.434	-0.076	16.310	0.016
0.6	2.148	1.416	-0.075	16.496	0.018
0.8	2.035	1.375	-0.071	15.634	0.021
1	1.959	1.323	-0.063	17.003	0.020
1.5	1.857	1.230	-0.048	15.819	0.017
2	1.786	1.155	-0.033	15.955	0.010
3	1.674	1.064	-0.013	16.350	-0.002
4	1.598	0.997	0.005	13.015	-0.009
5	1.538	0.942	0.024	10.380	-0.022
6	1.483	0.933	0.024	11.975	-0.020
8	1.405	0.902	0.034	13.828	-0.028
10	1.342	0.885	0.041	13.098	-0.033
15	1.254	0.845	0.058	14.249	-0.051

materials such as concretes [14–16], gaseous mixture [17], human tissues [18], soils and ceramic [19, 20] which showed

that the GP fitting is a very useful method for estimation of exposure and energy absorption build-up factors. Recently

TABLE 7: GP fitting parameters for BOM and COB.

Energy (MeV)	b	c	a	X_K	d
BOM					
0.015	1.020	0.379	0.231	11.998	-0.148
0.02	1.043	0.431	0.176	14.650	-0.084
0.03	1.143	0.394	0.213	14.390	-0.115
0.04	1.310	0.438	0.196	14.441	-0.109
0.05	1.519	0.515	0.164	14.678	-0.091
0.06	1.727	0.621	0.122	14.749	-0.067
0.08	2.135	0.759	0.081	13.507	-0.050
0.1	2.380	0.916	0.038	13.703	-0.042
0.15	2.561	1.171	-0.022	12.064	-0.016
0.2	2.548	1.296	-0.044	9.929	-0.010
0.3	2.419	1.397	-0.064	13.335	0.001
0.4	2.303	1.427	-0.073	18.953	0.015
0.5	2.211	1.423	-0.074	16.293	0.015
0.6	2.140	1.402	-0.072	17.362	0.016
0.8	2.032	1.362	-0.068	16.187	0.018
1	1.954	1.317	-0.062	16.346	0.019
1.5	1.846	1.230	-0.048	15.414	0.016
2	1.781	1.153	-0.032	15.316	0.009
3	1.673	1.058	-0.011	11.803	-0.002
4	1.605	0.979	0.011	12.405	-0.015
5	1.531	0.953	0.019	10.723	-0.017
6	1.482	0.933	0.025	12.246	-0.023
8	1.398	0.913	0.031	13.872	-0.027
10	1.336	0.897	0.039	13.047	-0.033
15	1.247	0.863	0.052	14.713	-0.049
COB					
0.015	1.017	0.296	0.321	10.490	-0.248
0.02	1.038	0.337	0.231	26.819	-0.340
0.03	1.106	0.376	0.225	13.775	-0.048
0.04	1.230	0.409	0.208	14.579	-0.116
0.05	1.388	0.465	0.187	14.455	-0.105
0.06	1.553	0.545	0.153	14.502	-0.085
0.08	1.846	0.706	0.093	14.638	-0.054
0.1	2.089	0.837	0.056	13.860	-0.042
0.15	2.342	1.074	-0.003	13.216	-0.023
0.2	2.398	1.206	-0.027	11.700	-0.017
0.3	2.330	1.327	-0.050	8.675	-0.010
0.4	2.247	1.361	-0.058	11.468	-0.003
0.5	2.159	1.387	-0.068	20.771	0.017
0.6	2.099	1.374	-0.067	18.708	0.015
0.8	2.002	1.344	-0.064	16.552	0.017
1	1.931	1.305	-0.059	15.991	0.014
1.5	1.834	1.224	-0.047	15.476	0.015
2	1.771	1.155	-0.033	14.576	0.010
3	1.670	1.058	-0.010	10.534	-0.003
4	1.593	0.997	0.006	14.562	-0.014
5	1.525	0.963	0.017	10.978	-0.016
6	1.475	0.945	0.022	13.346	-0.021
8	1.392	0.924	0.028	13.653	-0.025
10	1.332	0.905	0.037	13.208	-0.032
15	1.240	0.878	0.048	14.114	-0.045

the radiation shielding by fly-ash concretes [14] and building materials [21] has been reported.

The innovative bricks using the residual fly-ash are considered high-quality building materials by the manufacturers which will potentially decrease some of the negative environmental impact of coal-fired power generation while meeting increasing demands for greener building materials [22, 23]. Fly-ash brick (FAB), an environment-friendly cost-saving building product, is an alternative to burnt clay bricks. The FAB is approximately stronger than common bricks with consistent strength. The FABs are ideally suited for internal, external, load bearing, and nonload bearing walls. FABs are durable, economical, and eco-friendly and have low water absorption (8–12%), less mortar consumption, and low energy consumption with the lowest green house impact. These bricks are not affected by environmental conditions and remain static thus ensuring longer life of the building. These bricks are economical/cost-effective and nil wastage while transporting and handling. The houses and buildings in which people are living are constructed by the bricks made up of soil and environmental-friendly fly-ashes. The potential applications of fly-ash are shielding materials [24], glasses [25, 26], X-ray shielding [27], electromagnetic radiation in X-band and Ku-band shielding [28], and houses and building construction [22, 23].

In view of radiation safety inside the houses or buildings constructed by FAB, a theoretical gamma-ray exposure build-up factor (EBF) and fast neutron removal cross section have been calculated. We have calculated the EBF of eight types of FABs, brick of mud (BOM), and common brick (COB) by GP fitting in the photon energy range from 0.015 to 15 MeV up to 40 mfp. Comparative analysis shows that higher build-up factors exist for FABs and lower fast neutron removal cross sections. High EBF proves that FABs are poor gamma shielding for the construction of houses and buildings. The study reveals that brick of mud and common brick are low-cost safe building materials against radiation. It should be noted that this study is valuable in shielding analysis and estimation of emergency dose.

2. Computation Method

The elemental compositions of the fly-ash bricks are given in Table 1 [1]. These fly-ash bricks samples are prepared by a formula $(\text{Lime})_{0.15} (\text{Gypsum})_{0.05} (\text{Fly Ash}) \times (\text{Soil})_{0.8-x}$, where the values of x range from 0.4 to 0.7. Two other bricks of mud (BOM) and common brick (COM) are also analyzed for comparison of shielding properties for gamma-ray and neutron. The build-up calculation by GP fitting method and fast neutron removal cross section is explained below.

2.1. Exposure Build-Up Factor. The EBF of the bricks and the GP fitting parameters are calculated by method of interpolation from the equivalent atomic number, Z_{eq} , of the bricks. The computational work of these parameters is done in three steps as follows:

- (1) calculation of equivalent atomic number (Table 2),
- (2) calculation of GP fitting parameters (Tables 3, 4, 5, 6, and 7),
- (3) calculation of build-up factors.

TABLE 8: Fast neutron removal cross section of fly-ash brick and other bricks.

(a)										
Ele.	FAB1		FAB2		FAB		FAB4		FAB5	
	$\rho = 1.87 \text{ g cm}^{-3}$		$\rho = 1.81 \text{ g cm}^{-3}$		$\rho = 1.76 \text{ g cm}^{-3}$		$\rho = 1.72 \text{ g cm}^{-3}$		$\rho = 1.85 \text{ g cm}^{-3}$	
	Partial density	$\Sigma_R (\text{cm}^{-1})$	Partial density	$\Sigma_R (\text{cm}^{-1})$	Partial density	$\Sigma_R (\text{cm}^{-1})$	Partial density	$\Sigma_R (\text{cm}^{-1})$	Partial density	$\Sigma_R (\text{cm}^{-1})$
H	1.68E-03	1.01E-03	1.63E-03	9.74E-04	1.58E-03	9.47E-04	1.55E-03	9.26E-04	1.67E-03	9.96E-04
C	6.90E-02	3.46E-03	6.17E-02	3.10E-03	5.51E-02	2.77E-03	4.88E-02	2.45E-03	3.15E-02	1.58E-03
N	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
O	9.11E-01	3.69E-02	8.81E-01	3.57E-02	8.57E-01	3.47E-02	8.37E-01	3.39E-02	9.24E-01	3.74E-02
Na	1.87E-04	6.38E-06	1.81E-04	6.17E-06	1.76E-04	6.00E-06	1.72E-04	5.87E-06	2.04E-03	6.94E-05
Mg	2.00E-02	6.66E-04	1.86E-02	6.21E-04	1.74E-02	5.80E-04	1.62E-02	5.38E-04	1.42E-02	4.74E-04
Al	2.20E-01	6.45E-03	2.01E-01	5.90E-03	1.85E-01	5.42E-03	1.70E-01	4.97E-03	1.99E-01	5.84E-03
Si	4.34E-01	1.28E-02	4.18E-01	1.23E-02	4.04E-01	1.19E-02	3.93E-01	1.16E-02	4.64E-01	1.37E-02
P	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.30E-03	3.66E-05
S	7.48E-04	2.07E-05	7.24E-04	2.01E-05	5.28E-04	1.46E-05	5.16E-04	1.43E-05	3.70E-04	1.02E-05
K	7.85E-03	1.94E-04	1.45E-02	3.58E-04	2.08E-02	5.13E-04	2.68E-02	6.63E-04	8.14E-03	2.01E-04
Ca	1.29E-01	3.15E-03	1.23E-01	2.98E-03	1.16E-01	2.83E-03	1.11E-01	2.70E-03	1.35E-01	3.29E-03
Ti	1.87E-04	3.83E-06	1.81E-04	3.71E-06	1.76E-04	3.61E-06	1.72E-04	3.53E-06	1.05E-02	2.16E-04
Mn	1.87E-04	3.80E-06	1.81E-04	3.67E-06	1.76E-04	3.57E-06	1.72E-04	3.49E-06	1.85E-04	3.76E-06
Fe	7.61E-02	1.63E-03	8.96E-02	1.92E-03	1.03E-01	2.20E-03	1.16E-01	2.48E-03	5.77E-02	1.24E-03
Total	1.87	0.0663	1.81	0.0639	1.76	0.0619	1.72	0.0602	1.85	0.0651
(b)										
Ele.	FAB6		FAB7		FAB8		BOM		COB	
	$\rho = 1.79 \text{ g cm}^{-3}$		$\rho = 1.74 \text{ g cm}^{-3}$		$\rho = 1.70 \text{ g cm}^{-3}$		$\rho = 1.82 \text{ g cm}^{-3}$		$\rho = 1.87 \text{ g cm}^{-3}$	
	Partial density	$\Sigma_R (\text{cm}^{-1})$	Partial density	$\Sigma_R (\text{cm}^{-1})$	Partial density	$\Sigma_R (\text{cm}^{-1})$	Partial density	$\Sigma_R (\text{cm}^{-1})$	Partial density	$\Sigma_R (\text{cm}^{-1})$
H	1.61E-03	9.63E-04	1.57E-03	9.36E-04	1.53E-03	9.15E-04	0.00E+00	0.00E+00	4.49E-03	2.68E-03
C	3.04E-02	1.53E-03	2.96E-02	1.48E-03	2.89E-02	1.45E-03	0.00E+00	0.00E+00	1.12E-03	5.63E-05
N	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.87E-04	8.38E-06
O	8.91E-01	3.61E-02	8.62E-01	3.49E-02	8.39E-01	3.40E-02	9.93E-01	4.02E-02	8.48E-01	3.43E-02
Na	1.61E-03	5.49E-05	1.39E-03	4.74E-05	1.19E-03	4.06E-05	2.00E-03	6.82E-05	1.87E-04	6.38E-06
Mg	1.38E-02	4.59E-04	1.34E-02	4.46E-04	1.31E-02	4.36E-04	2.00E-03	6.66E-05	7.48E-04	2.49E-05
Al	1.84E-01	5.39E-03	1.70E-01	4.99E-03	1.58E-01	4.63E-03	9.01E-02	2.64E-03	1.47E-01	4.32E-03
Si	4.42E-01	1.30E-02	4.22E-01	1.25E-02	4.06E-01	1.20E-02	1.08E-01	3.20E-03	3.89E-01	1.15E-02
P	1.07E-03	3.04E-05	8.70E-04	2.46E-05	6.80E-04	1.92E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
S	3.58E-04	9.91E-06	3.48E-04	9.64E-06	3.40E-04	9.41E-06	0.00E+00	0.00E+00	3.74E-04	1.04E-05
K	1.47E-02	3.62E-04	2.09E-02	5.16E-04	2.67E-02	6.59E-04	0.00E+00	0.00E+00	4.97E-02	1.23E-03
Ca	1.27E-01	3.09E-03	1.20E-01	2.91E-03	1.13E-01	2.75E-03	6.19E-01	1.50E-02	8.88E-02	2.16E-03
Ti	8.77E-03	1.80E-04	7.13E-03	1.46E-04	5.61E-03	1.15E-04	0.00E+00	0.00E+00	1.68E-03	3.45E-05
Mn	1.79E-04	3.63E-06	1.74E-04	3.53E-06	1.70E-04	3.45E-06	0.00E+00	0.00E+00	3.18E-03	6.45E-05
Fe	7.43E-02	1.59E-03	8.99E-02	1.92E-03	1.05E-01	2.25E-03	5.46E-03	1.17E-04	3.36E-01	7.19E-03
Total	1.79	0.0628	1.74	0.0608	1.70	0.0593	1.82	0.0614	1.87	0.0636

Z_{eq} is a parameter which describes the material properties in terms of equivalent elements similar to atomic number for a single element. Since interaction processes of gamma-ray photon with matter, photo-electric absorption, Compton scattering, and pair-production are energy dependent, therefore Z_{eq} for each interaction varies according to the photon

energy. However the build-up of photons in the medium is mainly due to multiple scattering events by Compton scattering, so that Z_{eq} is derived from the Compton scattering interaction process.

The Z_{eq} , for individual brick, is estimated by the ratio of $(\mu/\rho)_{\text{Compton}}/(\mu/\rho)_{\text{Total}}$, at a specific energy with the

FIGURE 1: Exposure build-up factors for water by ANS-6.4.3, MCNP-5, and GP fitting.

correspondance of an element at the same energy. Thus first the Compton partial mass attenuation coefficient, $(\mu/\rho)_{\text{Compton}}$, and the total mass attenuation coefficients, $(\mu/\rho)_{\text{Total}}$, are obtained for elements $Z = 4$ to 40 for the selected bricks in the energy region from 0.0015 to 15 MeV using WinXCom [29, 30].

The interpolation of Z_{eq} is employed by the following formula [31, 32]:

$$Z_{\text{eq}} = \frac{Z_1 (\log R_2 - \log R_1) + Z_2 (\log R - \log R_1)}{\log R_2 - \log R_1}, \quad (1)$$

where Z_1 and Z_2 are the atomic numbers of the elements corresponding to the ratios R_1 and R_2 , respectively. R is the ratio, $(\mu/\rho)_{\text{Compton}}/(\mu/\rho)_{\text{Total}}$, at specific energy and the ratio $(\mu/\rho)_{\text{Compton}}/(\mu/\rho)_{\text{Total}}$ for Z_{eq} lies between two successive ratios of the elements.

The GP fitting parameters are calculated in a similar fashion of interpolation procedure for Z_{eq} . The GP fitting parameters for the elements were taken from the ANS-6.4.3 standard reference database which provides the GP fitting parameters for twenty three elements ($Z = 4$ to 92) in the energy region from 0.015 to 15 MeV up to 40 mfp penetration depth. The GP fitting parameters for the bricks were interpolated using a similar formula:

$$C = \frac{C_1 (\log Z_2 - \log Z_{\text{eq}}) + C_2 (\log Z_{\text{eq}} - \log Z_1)}{\log Z_2 - \log Z_1}, \quad (2)$$

where C_1 and C_2 are the values of the GP fitting parameters corresponding to the atomic numbers of Z_1 and Z_2 , respectively, at a given energy.

The third and final step is build-up factors estimation by GP fitting parameters (b , c , a , X_K , and d) in the photon

energy range of 0.015–15 MeV up to a 40 mfp by the following equations [13]:

$$\begin{aligned} B(E, X) &= 1 + \frac{b-1}{K-1} (K^x - 1) \quad \text{for } K \neq 1, \\ B(E, X) &= 1 + (b-1)X \quad \text{for } K = 1, \\ K(E, X) &= CX^a + d \frac{\tanh(X/X_K - 2) - \tanh(-2)}{1 - \tanh(-2)} \end{aligned} \quad (3)$$

for penetration depth $(X) \leq 40$ mfp,

where X is the source-detector distance for the medium in terms of mfp and b the value of the exposure build-up factor at 1 mfp, $K(E, X)$ is the dose multiplicative factor, and b , c , a , X_K , and d are computed GP fitting parameters which depend on the attenuating medium and source energy.

2.2. Fast Neutron Removal Cross Section. An approximate method for calculation of the attenuation of fast neutrons by use of an effective removal cross section has been developed to allow for scattering or build-up. The effective removal crosssection for compounds and homogenous mixtures may be calculated from the value of Σ_R (cm^{-1}) or Σ_R/ρ (cm^2/g) for various elements in the compounds by mixture rule. Difference in application of mixture for neutron interaction differs as weight fraction is replaced by partial density and mass attenuation coefficient by neutron removal cross section:

$$\begin{aligned} \frac{\Sigma_R}{\rho} &= \sum_i w_i \left(\frac{\Sigma_R}{\rho} \right)_i, \\ \frac{\Sigma_R}{\rho} &= \sum_i \rho_i \left(\frac{\Sigma_R}{\rho} \right)_i. \end{aligned} \quad (4)$$

The values obtained for effective neutron removal cross section by the above equations are accurate within 10% of the experimental values investigated for aluminium, beryllium, graphite, hydrogen, iron, lead, oxygen, boron carbide, and so forth [33]. The Σ_R/ρ values of elements of the bricks have been taken from Kaplan and Chilton et al. [34, 35].

3. Uncertainties

The uncertainties in the build-up factor estimated by GP fitting are comparable with ANS-6.4.3 standard and MCNP-5 [36] for air and water. Figure 1 shows that the EBFs in water by GP fitting, ANS-6.4.3 standard, and MCNP-5 at different photon energies are comparable. The MCNP-5 results vary from those ANS-6.4.3 standards with greatest 13.83% due to difference in cross section libraries, method of solution for codes, calculation methods, standard deviation, and physics assumptions for bremsstrahlung and coherent scattering [36]. It is found that the invariant embedding, GP fitting, and MCNP simulation are in good agreement with 18 low- Z materials with small discrepancies [12]. This quantitative and comparative approach shows that our results for gamma-ray EBF will be of small uncertainties for easy establishment of the data and analysis by GP fitting methodology.

FIGURE 2: Continued.

FIGURE 2: Variation of exposure build-up factor of fly-ash bricks, brick of mud, and common brick with incident photon energy.

4. Result and Discussion

The photon energy dependency of the EBFs is shown in Figure 2 at various penetration depths (0.5, 5, 10, 20, 30, and 40 mfp) for each FAB, BOM, and COB. Variation of EBF with penetration depths is shown in Figure 3 at photon energies 0.015, 0.15, 1.5, and 15 MeV. The chemical compositions of the selected materials are investigated at penetration depths of 0.5, 5, 10, 20, 30, and 40 mfp and shown in Figure 4. The fast neutron removal cross sections of the studies bricks are given in Tables 8(a) and 8(b). The variation of EBF with photon energy, penetration depth, and chemical compositions is explained in next coming sections.

4.1. Photon Energy Dependency of Exposure Build-Up Factor.

The variation of EBF values of the FAB, BOM, and COB with photon energy is shown in Figure 2. It is noted that the EBF values of the bricks are minimum in low-energy and high-energy photons whereas they are higher in the intermediate-energy photons. The build-up factor in low-energy is small because the photons are completely absorbed by photo-electric absorption, gradually increases with the energy due to multiple scattering by the Compton scattering in the intermediate-energy region and finally again reduces in high-energy region due to pair-production. The analysis shows that the brick having, lowest EBF should be considered for gamma-ray shielding. The gamma build-up factors are the lowest for 0.5 mfp, and highest for 40 mfp, due to multiple scattering events for large penetration depth of 40 mfp. The EBFs of the FAB, BOM, and COB are found higher than the ordinary concretes [16].

4.2. Penetration Depth Dependency of Exposure Build-Up Factor. The variation of EBFs of the selected FABs, BOM, and COB with penetration depths at photon energies 0.015, 1.5, 5, and 15 MeV is shown in Figure 3. It is observed that the EBF values increase with the penetration depth initially

and afterwards become stable. The EBFs for the BOM and COB are found lesser than FABs at photon energies 0.15, 0.15, and 1.5 MeV photon energy. It can be seen that the values of EBF of the bricks increase with increase in Z_{eq} at 15 MeV as penetration depth increases. In the low photon energy region (~ 1.5 MeV), exposure build-up factor becomes independent of penetration depth above 25 mfp. The reason may be that beyond 3 MeV, the pair-production dominates the Compton scattering and produces the electron-positron pairs. These particles may escape from the medium of lower penetration depth whereas they will scatter in large penetration depths as well as originate the secondary gamma photon by annihilation to increase the gamma photon intensities. The smallest value of EBFs of COB for low energy (< 1.22 MeV) gradually increases with increase in photon energy due pair-production.

4.3. Chemical Composition Dependency of Exposure Build-Up Factor.

The EBFs are dependent on the atomic number of elements; hence EBF values of the materials are dependent on chemical compositions [16]. The chemical element composition dependency on the EBF is analyzed by for the photon energy at constant penetration depths as shown in Figure 4. It is observed that the EBF values are small at low- as well as high-energy photons whereas maximum in the intermediate-energy photons. The reason for peaked EBF values is that the photo-electric and pair-production are dominant interaction processes in low- and high-energy, respectively, which completely remove the photons. The intermediate-energy photon takes over Compton scattering where photon goes under multiple scattering events to build-up the exposure. The brick materials having large weight fraction of low-Z elements are showing high EBF values due to less removal of the photons.

The fly-ash brick (low Z_{eq}) is having larger EBF compared with other bricks (higher Z_{eq}) for entire energy region from 0.015 to 15 MeV in low penetration depths. The EBF of

FIGURE 3: Variation of exposure build-up factor of fly-ash bricks, brick of mud, and common brick with penetration depth for photon energies 0.015, 0.15, 1.5, and 15 MeV.

BOM and COB shows behavior in reverse order at 3 MeV for large penetration depth. Above 3 MeV photon energy and for large penetration depths (above 10 mfp), exposure build-up factor becomes directly proportional to Z_{eq} . It may be due to dominance of pair-production above 1.22 MeV which increases with increase in photon energy and results in production of electron and positron. The positron annihilates at zero kinetic energy and produces new two photons of energy 0.511 MeV which build-up in the medium due to multiple scattering events. The pair-production dependent on Z^2 signifies that the COB and BOM should have large photon intensities of energies 0.511 MeV. The EBF is found large in the higher penetration depths due to possibilities of multiple scattering whereas the positron may escape though the low penetration depth.

4.4. Fast Neutron Removal Cross Section. In case of neutron attenuation, the effective fast neutron removal (FNR) cross sections of the different FAB, BOM, and COB are given in Tables 8(a) and 8(b). The effective removal cross section is approximately constant for neutron energy from 2 to 12 MeV [34]. In Tables 8(a) and 8(b), the calculations are being listed for various elemental compositions of the FAB and other bricks. The effective FNR cross section Σ_R (cm^{-1}) of the selected brick materials is calculated by partial density of each element and FNR cross section. It is observed that the removal cross section is higher for FAB1, and this leads to the conclusion that the FAB1 is more effective for neutron attenuation than the FABs, BOM, and COB. Also, from point of neutron shielding, fly-ash and common brick materials are more suitable replacement of brick of mud. The low

FIGURE 4: Variation of exposure build-up factor of fly-ash bricks, brick of mud, and common brick with photon energy for penetration depths 0.5, 5, 10, 20, 30, and 40 mfp.

variation in removal cross section is being noticed for all types of the bricks. Elevated values of removal cross section of FABI and COB are attributed due to high density and large contribution of low atomic number weight fractions of H and C. With constant H weight fraction and variable densities, the removal cross section varies. In cases of COB, the removal cross section is slightly higher due to large C weight fraction with equal value of density of FABI. Therefore it is concluded that low atomic number elemental composition and density contribute a vital role in gamma-ray and neutron shielding properties.

5. Conclusions

In the present studies, we have calculated the exposure build-up factors of fly-ash bricks for photon energies from 0.015 to 15 MeV up to 40 mfp penetration depth by geometrical progression (GP) method. Exposure build-up factor increases with the increase in penetration depth for all the fly-ash bricks. For the entire energy region (0.015–15.0 MeV), in case of small penetration depths (below 10 mfp), exposure build-up factor is inversely proportional to the Z_{eq} . In the low photon energy region (≈ 1.5 MeV), exposure build-up factor becomes dependent upon penetration depth above 25 mfp. Above 3 MeV photon energy and for large penetration depths (above 10 mfp), exposure build-up factor becomes directly proportional to Z_{eq} . Bricks containing low atomic number elements show high fast neutron removal cross. Low atomic number elemental composition and density contribute a vital role in gamma-ray and neutron shielding properties. The study should be very useful for shielding effectiveness of fly-ash bricks and dose estimation.

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