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Immobilization of Molybdenum in Ordinary Portland Cement

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Abstract

In this paper we report the results of the studies concerning the addition of varying concentrations of molybdenum on physical, chemical and engineering properties of 43 grade ordinary Portland cement. The studies regarding initial and final setting time of cement, bulk density, compressive strength, microscopic and spectroscopic properties have been carried out and the result of these studies are presented and discussed. Different building products containing varying concentrations of added molybdenum were prepared and subjected to hydrologic environment to investigate the leaching behavior of molybdate ions. The efforts have also been made to establish a quantitative co-relation between the concentration of added molybdenum and the intensity of any effect in above properties of the cement. Also the possible fixation mechanism of molybdenum in cement is suggested. The X-ray diffraction analysis of molybdenum added cement sample was carried out and it was observed that the insoluble molybdenum is distributed in Portland cement in the form of powellite ($CaMoO_4$).

Keywords: Cement; Heavy metals; Molybdenum; Setting time; Waste management

Introduction

The protection of public health and the environment from the hazardous pollutants is a major concern of industrialized nations [1-3]. One of the most toxic forms of inorganic industrial waste is that contains toxic heavy metals. This type of waste is generated from metallurgical, mining, chemical, leather industry, distillery, sugar, battery, electroplating and pigment industry. Generally the metal concentration in the waste is too low for economical recovery but high enough to represent toxicity hazards. Therefore, these industries discharge their waste without treatment or with improper treatment in the landfills. Its disposal in hydrologic environment can cause environmental risk due to the mobility of metal ions [4]. These metal ions get mixed in surface water and ground water system, which may be detrimental to human being as well to the environment. Molybdenum is frequently used in alloy industry and in the manufacturing of electronic devices owing to its high melting point, high strength at elevated temperature, high thermal conductivity and good resistant to corrosion. It is also used as a catalyst in many petrochemical and inorganic reactions in solutions. Molybdenum generally occurs in form of molybdate ions ($MoO^4{}_2$-) at about pH 5 and above. Various technologies have been developed which purport to render a waste or to reduce the potential for the release of toxic species into the environment. Molybdenum containing waste can be immobilized in cement based binder system [5-7]. This technique is used to transform potentially hazardous liquid or solid waste into less hazardous and or non-hazardous solid before disposal in a landfill, thus preventing the waste from contaminating the environment [7-13]. The United State Environmental Protection Agency also recognizes cementitious Solidification/Stabilization as "the Best Demonstrated Available Technology for land disposal of most toxic elements [14]. Many formulations have been developed for the S/S process according to the kinds of wastes. Portland cement can be modified for suitable S/S process using fly ash, lime slag soluble silicates etc. [15-23]. One of the most difficult problems in this process is that the hydration of cementitious materials is too retarded to set and harden enough due to the inhibition of hydration reaction of heavy metals in a landfill area. It seems that Solidification/Stabilization (S/S) process would be the best practical technology to treat the molybdenum containing waste. There is very less data reported in the literature about the effects of addition of molybdenum on various properties of cement. Therefore, efforts have been made to fill void in this data. The results of these studies on the effects of addition of molybdenum on various properties of 43 grade ordinary Portland cement are presented and discussed in this paper. A quantitative co relation between the concentration of molybdenum added and the intensity of any effect has been established.

Materials, Apparatus and Methods

Materials

Sodium molybdate (GR) from Loba, India was used for this study. Commercial ordinary Portland cement 43 grade was used. Molybdenum has been added to the ordinary Portland cement in the different concentrations of molybdate ions. All solutions were prepared in double distilled water. Fly ash is also used as a filler material with the ordinary Portland cement to make mortar samples as fly ash is treated as industrial waste which does not have any cementing property itself but in the presence of lime and water it behaves like cement.

Apparatus

Atomic Absorption Spectrophotometer (AAS) from Hitachi (Z-7000) was used to determine the metal ion concentrations. Hazardous waste filtration system from Millipore (YT-30142 HW) was used to carry out Toxicity Characteristic Leaching Procedure as recommended by United State Environment Protection Agency (USEPA); UV-Visible spectrophotometer (Aquamate) from Thermo Corporation was used for spectrophotometric studies. Vicat apparatus was used to determine initial and final setting time of control cement as well as metal ion doped cement samples. Compressive strength testing machine from Central Scientific Instruments Company was used to determine the compressive

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strength of mortar samples. Scanning Electron Microscope (SEM) from LEO 438VP, UK was used for the microstructure visualization of fractured cement surfaces. X-Ray powder diffraction analysis was carried out by using the instrument from Rikagu, UK to identify the crystalline phases present in the control as well as in metal containing cement samples.

Methods

The chemical analysis of the cement was carried out according to Indian standard specifications IS: 4032:1985 guidelines. The physical properties were tested according to the Indian standard specification IS: 4031:1996 guidelines. The chemical composition and physical properties of Ordinary Portland Cement used are summarized in Tables 1 and 2 respectively.

Preparation of cement pastes and mortars: The Initial and final setting times of control as well as the cement samples, containing varying concentrations of molybdenum, were determined by following the methods as described in IS: 4031:1996. The results obtained for controls were compared with those obtained for molybdenum containing samples to know the effect of addition of molybdenum on the setting time of cement paste. To investigate the effect of addition of molybdenum on engineering properties like compressive strength, bulk density of mortar samples containing cement and fly ash, were cast in 2.78” cubic iron molds. The samples were demolded after 24 hours and were dipped into water for curing the compressive strength of the cubes were determined on 3, 7, 28, 60, 90, 180 and 360 day of curing. Six samples were taken each time and the average value of these results was reported.

X-ray diffraction analysis: It is possible to find and quantify crystalline components which have over 1% abundance in a sample If the correct experimental technique are used. XRD can give a semi quantitative or quantitative analysis of the components of the crystalline fraction. Thus XRD gives most information from the crystalline components of the material under investigation. X-ray diffraction analysis was performed with a Rigaku, Japan (Dmax 2200 VK/PC) automated X-ray diffractometer. The samples were crushed to a fine powder with porcelain and sieved through a 45 mm sieve. The XRD scan was made with copper ka radiation from 3°-70° 2θ with 0.02° step width and 1 to 3 s counting time.

Scanning electron microscopy: Scanning Electron Microscopy (SEM) is a technique used to know the fractured surface of cementitious material and of three dimensional particle level morphology. It is

Constituent	Weight percentage
Silica	20.80
Aluminum oxide	4.40
Iron oxide	3.79
Calcium oxide	66.10
Magnesium oxide	3.30
Anhyd. Sulfuric acid	3.00
Sodium oxide	0.20
Potassium oxide	0.70

Table 1: Chemical composition of cement.

Physical parameter	Results
Loss on ignition	0.7 %
Consistency	31.58 %
Soundness	1.0 mm
Bulk density	1.421g/cm3
Initial setting time	175 min.
Final setting time	300 min

Table 2: Physical properties of cement.

S. No.	Concentration of metal ion (ppm)	IST	FST
1.	--	175	300
2.	1	180	300
3.	5	180	300
4.	10	170	300
5.	100	170	310
6.	1000	170	300
7.	1500	155	275
8.	2000	135	265
9.	3000	135	265
10.	5000	135	265

IST- Initial setting time of cement in min.
FST- Final setting time of cement in min.

Table 3: Effect of fixation of molybdenum on initial and final setting time of cement.

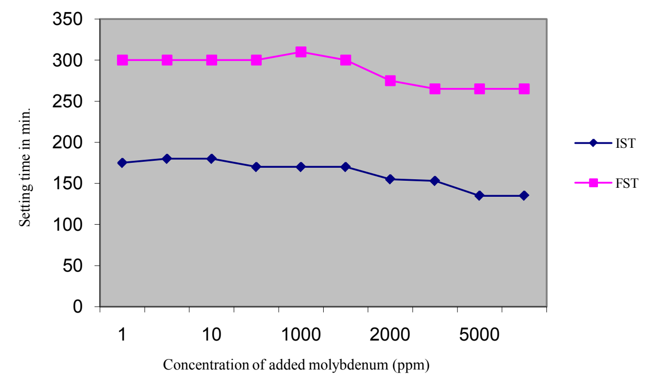

Figure 1: Effect of fixation of molybdenum on the setting time of cement.

Binder system	No. of days	Average bulk density (+ 0.001 g/cm³) Molybdenum			
		Control	1000 ppm	1500 ppm	2000 ppm
Cement + fly ash	1	2.303	2.385	2.393	2.398
	28	2.381	2.385	2.393	2.399

Table 4: Average bulk density values of solidified products on 1 and 28 days of curing.

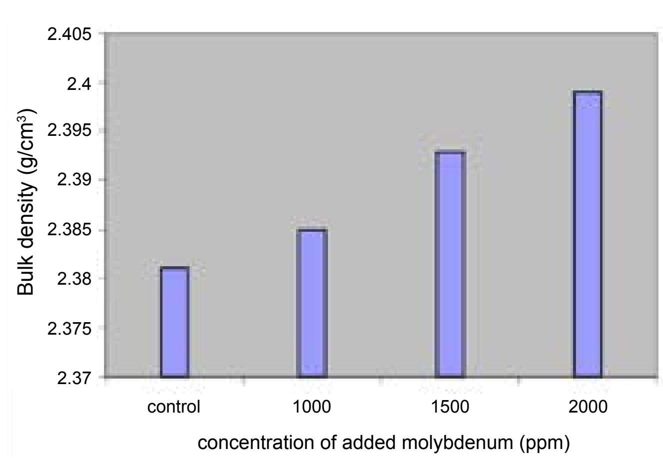

Figure 2: Bulk density of control and molybdenum on 28 day of curing.

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Added molybdenum (ppm)	No. of days						% change in compressive strength in comparison of control					
	3	7	28	60	90	180	3	7	28	60	90	180
Control	323.4	436.0	486.0	570.0	570.0	620.0						
1000	345.0	410.0	550.0	555.0	555.0	606.6	106.6	93.9	113.0	97.3	97.3	97.8
1500	354.0	423.4	580.0	592.0	640.0	660.0	96.9	119.1	103.8	112.2	106.4	109.4
2000	354.0	426.6	590.0	564.0	640.0	700.0	109.4	97.7	121.2	98.9	112.2	112.9

Table 5: Compressive strength (kg/cm^2) of mortar samples.

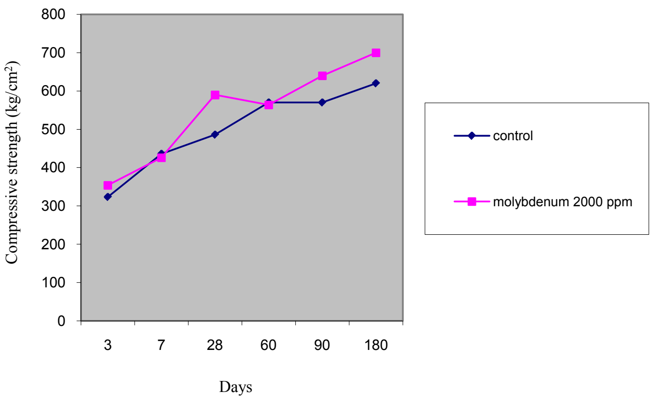

Figure 3: Effect of addition of 2000 ppm molybdenum on the compressive strength of cement.

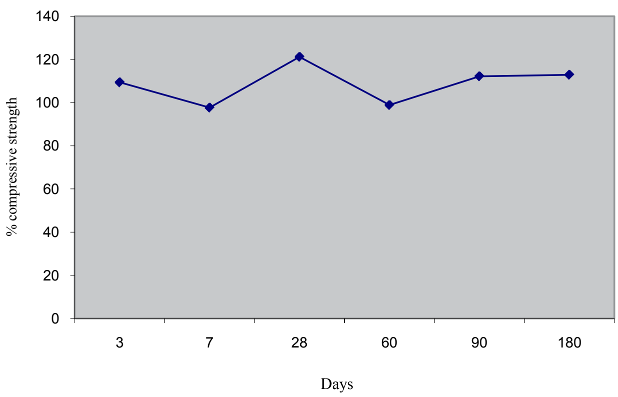

Figure 4: Percentage change in compressive strength of molybdenum 2000 ppm containing samples in comparison with control.

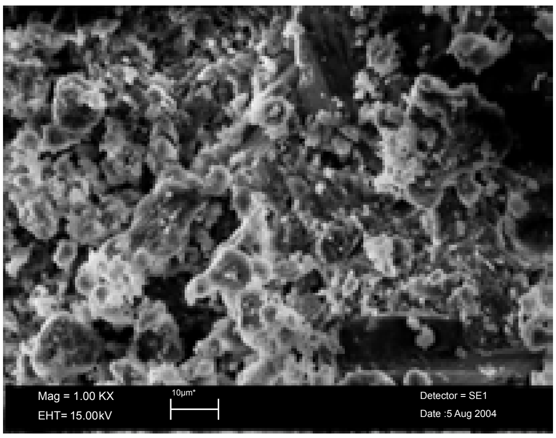

Figure 5: SEM image of pure cement sample on 28 day of curing.

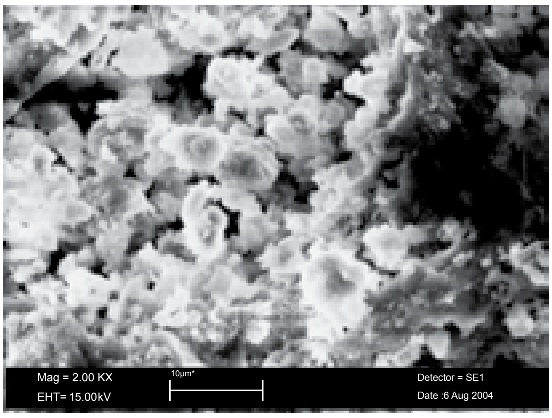

Figure 6: SEM image of molybdenum 2000 ppm containing cement sample on 28 day of curing.

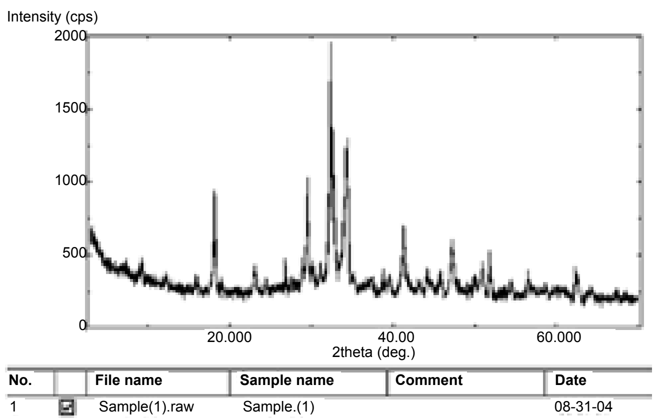

Figure 7: X-Ray diffractogram of molybdenum 2000 ppm containing cement sample.

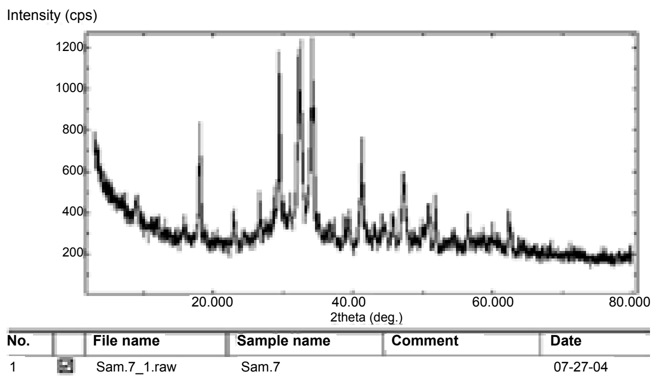

Figure 8: X-Ray diffractogram of Blank cement sample.

molybdenum-2000 ppm							
PEAK: 21-pts/Parabolic Filter, Threshold=3.0, Cutoff=0.1%, BG=3/1.0, Peak-Top=Summit							
2-Theta d(A)	**BG**	**Height**	**I%**	**Area**	**I%**	**FWHM**	
7.131	12.3865	223	52	5.4	1137	7.4	0.372
7.339	12.0347	228	55	5.7	449	2.9	0.139
9.223	9.5807	194	95	9.9	1507	9.8	0.270
12.244	7.2229	169	63	6.6	958	6.2	0.259
15.939	5.5556	145	67	7.0	1404	9.1	0.356
18.142	4.8858	151	415	43.4	5679	36.9	0.233
19.019	4.6624	153	58	6.1	464	3.0	0.136
23.081	3.8502	144	113	11.8	1727	11.2	0.260
24.516	3.6280	153	46	4.8	542	3.5	0.200
26.822	3.3212	160	126	13.2	820	5.3	0.111
27.591	3.2303	160	55	5.7	823	5.3	0.254
28.839	**3.0932**	**203**	**87**	**9.1**	**685**	**4.4**	**0.134**
29.539	3.0215	183	433	45.2	7693	50.0	0.302
30.200	2.9569	205	73	7.6	494	3.2	0.115
31.182	2.8660	203	69	7.2	347	2.3	0.085
32.318	2.7678	220	957	100.0	15399	100.0	0.274
32.660	2.7395	225	586	61.2	11339	73.6	0.329
33.680	2.6589	222	85	8.9	3446	22.4	0.689
34.419	**2.6035**	**213**	**568**	**59.4**	**13572**	**88.1**	**0.406**
36.818	2.4392	155	52	5.4	1825	11.9	0.597
37.460	2.3988	157	56	5.9	938	6.1	0.285
38.836	2.3169	148	93	9.7	1145	7.4	0.209
39.503	2.2793	152	69	7.2	1037	6.7	0.255
41.258	2.1863	157	261	27.3	6028	39.1	0.393
43.344	2.0858	152	44	4.6	453	2.9	0.175
44.303	2.0429	149	87	9.1	2099	13.6	0.410
45.846	1.9776	155	83	8.7	1044	6.8	0.214
47.281	**1.9209**	**149**	**211**	**22.0**	**5459**	**35.5**	**0.440**
50.020	1.8220	161	60	6.3	591	3.8	0.167
50.919	1.7919	151	107	11.2	1923	12.5	0.306
51.821	1.7628	136	179	18.7	2104	13.7	0.200
54.456	**1.6836**	**140**	**47**	**4.9**	**476**	**3.1**	**0.172**
56.503	1.6273	140	96	10.0	1545	10.0	0.274
58.802	1.5690	128	57	6.0	1223	7.9	0.365
59.467	1.5531	131	46	4.8	798	5.2	0.295
62.302	1.4891	118	134	14.0	2962	19.2	0.376
62.518	1.4844	117	103	10.8	2949	19.2	0.487
64.278	1.4480	119	54	5.6	1291	8.4	0.406
67.453	1.3873	120	46	4.8	558	3.6	0.206

Table 6: Peak Search Report (39 Peaks, Max P/N = 13.9)

generally used to magnify an image. It can magnify image up to three lack times. There are Three types of rays emitted from the instruments that is back scattered electron rays, secondary rays. Both are used for imaging. And X-rays are used for elemental analysis of the sample. It is used for conducting material for non-conducting and biological material like cement coat a conducting material on it. It may be carbon or gold.

Leaching studies: A suitable way to know the effectiveness of the immobilization of contaminants after solidification process is to perform the extraction test. Usually this test is performed under the chosen condition of leaching medium. Standard method No.1311 recommended by United State Environment Protection Agency is followed. Crushed solid material has been taken in hazardous waste filtration system with zero head space extractor. A measured volume of water was added and this assembly has been shaken for 18 hours continuously in agitation assembly. Filtered extract was collected in a closed vessel and analyzed for metal concentration by using Atomic Absorption Spectrophotometer. The results were compared with that of blank samples to know the actual enhancement of the particular metal in the leachate. It was observed that the leachate of the samples doped with 1000, 1500 and 2000 ppm molybdenum contain 2.5, 3.0 and 11.0 ppm molybdenum respectively. It is clear that the presence of all molybdenum in the leachate is due to the molybdenum containing samples because molybdenum concentration level in leachate of control cement samples is below the detection limit.

Results and Discussion

Although hydration of cement begins immediately as water is added into it but there is a period of time-several hours in which cement remains in fluid like state before setting as a rigid, load bearing material. Setting refers the change of state from fluid paste to rigid form. According to IS: 8112:1996. The initial setting time of a 43 grade ordinary Portland cement should be at least 30 min. and final setting time should be within 600 min. The initial and final setting time of control as well as molybdenum containing samples were determined and presented in Table 3. Molybdenum was added in the concentrations 1, 5, 10, 100, 1000, 1500, 2000, 3000 and 5000 ppm respectively. A perusal of data shows that there is no considerable effect of molybdenum addition on initial as well as final setting time up to the concentration 1000 ppm. The maximum change in this parameter was observed within the concentration range 1000-2000 ppm molybdenum (Figure 1). The setting time became stable beyond this concentration limit. The effect of molybdenum addition on setting time of cement was recorded directly proportional to the concentration of molybdenum added. All the experiments were carried out in triplicate to assure accuracy and reproducibility. All the samples were observed for any visual change before the compressive strength testing each time. There was no significant change found in colour and shape except the surface of molybdenum containing samples was smoother than that of control samples.

Bulk density of control samples as well as molybdenum containing samples was determined on 28 day of curing. Six samples were taken each time and the average value of these observations was reported. There was no significant change in this parameter for molybdenum containing sample in comparison with control (Table 4). Bulk density of control samples was 2.381 ± 0.001 g/cm^3, while it changed to 2.385, 2.393 and 2.399 ± 0.001 g/cm^3 for 1000, 1500 and 2000 ppm molybdenum containing samples respectively (Figure 2). The figure shows that bulk density values of molybdenum containing samples increased with the increase in concentration of molybdenum although the change is in significant. Compressive strength of control mortar samples as well as molybdenum containing samples was determined on 3, 7, 28, 60, 90, 180 and 360 days of curing. All the values have been taken in triplicate and the average values have been reported. The

[Sam.5_1.raw] Sam. Blank							
PEAK: 23-pts/Parabolic Filter, Threshold=3.0, Cutoff=0.1%, BG=3/1.0, Peak-Top=Summit							
2-Theta d(A)	BG	Height	I%	Area	I%	FWHM	
9.081	9.7305	215	77	14.6	1728	13.5	0.382
12.272	7.2065	186	47	8.9	337	2.6	0.122
13.090	6.7578	168	56	10.6	459	3.6	0.139
14.835	5.9667	153	47	8.9	278	2.2	0.101
15.819	5.5976	153	81	15.4	1576	12.4	0.331
18.058	4.9083	168	335	63.7	4605	36.1	0.234
18.961	4.6766	158	49	9.3	560	4.4	0.194
23.001	3.8634	142	97	18.4	2045	16.0	0.358
26.658	3.3411	172	129	24.5	1773	13.9	0.234
27.514	3.2391	177	47	8.9	465	3.6	0.168
29.420	3.0335	208	500	95.1	7966	62.4	0.271
31.043	2.8785	212	69	13.1	745	5.8	0.184
32.160	2.7810	224	491	93.3	12756	100.0	0.442
32.579	2.7462	243	500	95.1	10704	83.9	0.364
34.121	2.6255	222	526	100.0	11840	92.8	0.383
36.636	2.4508	161	59	11.2	1696	13.3	0.489
37.242	2.4123	158	48	9.1	592	4.6	0.210
38.741	2.3224	158	80	15.2	630	4.9	0.134
39.421	2.2839	144	105	20.0	2290	18.0	0.371
41.242	2.1871	154	303	57.6	6325	49.6	0.355
41.645	2.1669	164	69	13.1	1658	13.0	0.408
44.081	2.0526	152	83	15.8	2253	17.7	0.461
44.679	2.0266	156	58	11.0	1749	13.7	0.513
45.798	1.9796	150	92	17.5	1599	12.5	0.295
47.140	1.9263	148	208	39.5	6343	49.7	0.518
49.865	1.8273	169	55	10.5	458	3.6	0.142
50.803	1.7957	164	103	19.6	1485	11.6	0.245
51.724	1.7659	137	156	29.7	1981	15.5	0.216
54.516	1.6819	139	57	10.8	751	5.9	0.224
56.453	1.6287	149	90	17.1	1114	8.7	0.210
58.593	1.5741	147	53	10.1	447	3.5	0.143
59.912	1.5426	146	69	13.1	450	3.5	0.111
62.380	1.4874	123	120	22.8	2553	20.0	0.362
63.710	1.4595	122	51	9.7	434	3.4	0.145
64.265	1.4482	122	40	7.6	786	6.2	0.334
71.050	1.3257	115	40	7.6	271	2.1	0.115
62.518	1.4844	117	103	10.8	2949	19.2	0.487
64.278	1.4480	119	54	5.6	1291	8.4	0.406
67.453	1.3873	120	46	4.8	558	3.6	0.206

Table 7: Peak Search Report (36 Peaks, Max P/N = 9.6).

results of this study are presented in Table 5. It is important to mention that according to IS:1882:1989 the compressive strength of 43 grade ordinary Portland cement should be at least 230 kg/cm^2, 330 kg/cm^2 and 430 kg/cm^2 for 3, 7 and 28 days of curing. Compressive Strength is the most common performance measures by compression testing machine. The compressive strength is calculated from the failure load divided by the cross section area resisting the load. It is reported in units of kg/cm^2.

The addition of molybdenum caused considerable change on the rate of strength attainment as well as on the compressive strength of the binder system. Utmost care was taken to reduce variability associated with batch preparation step and reagent addition to avoid any substantial variability within a batch. A perusal of data presented in Table 5, exhibits that compressive strength of molybdenum containing samples increases significantly in comparison with control sample. The effect intensifies as the concentration of added molybdenum is increased (Figures 3 and 4).

Microscopic and spectroscopic analysis of the cement paste

The microstructures of hardened control cement paste as well as molybdate containing cement paste were investigated by Scanning Electron Microscopy (Figures 5 and 6). The microstructure of all these samples was very compact with gel like C-S-H phase as a main component. It is clear from scanning electron microscopy images that in molybdenum dopped samples the C-S-H phase is more densified than that of control samples. The XRD diffractogram of sample containing molybdenum and blank sample are presented in Figures 7 and 8. It has been found that the intensity of powellite mineral is clearly indicated in the diffractogram. The presence of molybdenum reduced the leaching of Ca through the solidification process. Molybdenum is mostly dissolved in the interstitial phases while very small amount is found in the silicate phase The X-Ray diffraction study shows that the insoluble molybdenum found in the cement as powellite form $CaMoO_4$. The enclosed peak search reports shows that peaks of Powellite mineral ($CaMoO_4$) are present in the X-ray pattern characteristics (Tables 6 and 7).

Conclusions

The effect of fixation of molybdenum on physical, chemical and engineering properties of 43-grade Ordinary Portland Cement was studied. A quantitative correlation between the concentrations of molybdenum used and the intensity of any change in the properties of 43 grade Ordinary Portland Cement like initial and final setting time, compressive strength, bulk density, leaching studies, microscopic and spectroscopic studies etc. has been established. Molybdenum was used in the concentration range 1 ppm-5000 ppm. It is evident from the results obtained that molybdenum addition improves setting and hardening characteristics of the cement. The compressive strength of the cement improves to 110.5% on 28 day of curing for 2000 ppm of molybdenum addition. SEM studies show that the density of C-S-H gel is more in molybdenum doped cement samples in comparison with control. The presence of peaks of powellite ($CaMoO_4$) in X-ray diffractogram of molybdenum doped cement samples suggested that molybdate ions combine with calcium ions to give $CaMoO_4$ and get fixed chemically.

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References

1. Park CK (2000) Hydration and solidification of Hazardous waste containing heavy metals using modified cementitious materials. Cem Conc Res 30: 429-435.
2. Cote' PO, Bridle TR, Hamilton DP (1984) Evaluation of Pollutant Release from Solidified Aqueous Waste Using a Dynamic Leaching Test. Hazardous Waste and Environmental Emergencies, Houston TX.
3. Glasser FP (1993) Chemistry of cement solidified waste forms chemistry and microstructure of solid waste forms, Lewis publishers Chelsea, MI-P.I.
4. Nocun W, Goteborg JM (1997) Studies on Immobilization of heavy metals in Cement Paste-C-S-H leaching behavior. Proceedings of the 10th international Congress on the chemistry of cement, Sweden.
5. Kindness A, Lachowski EE, Minocha AK, Glasser FP (1994) Immobilization and Fixation of Molybdenum (VI) by Portland cement. Waste Management 14: 97-102.
6. Kasselouri V, Ftikos Ch (1997) The effect of MoO_3 on the C3S and C3A formation. Cem Conc Res 27: 917-923.
7. Duchesne J, Laforest G (2004) Evaluation of the degree of Cr ions immobilization by different binders. Cem Conc Res 34: 1173-1177.
8. Mayers TE, Eappi ME (1992) Laboratory evaluation of Stabilization/ Solidification technology for reducing the mobility of heavy metals in New Bedford harbor superfund site sediment stabilization of hazardous radioactive and mixed wastes, 2nd Edn. ASTM publication Philadelphia PA: 304.
9. Adaska WA, Tresouthick SW, West PB (1991) Solidification and Stabilization of wastes using Portland cement. Portland cement Association Skokie IL.
10. Deja J (2002) Immobilization of Cr6+, Cd2+, Zn2+ and Pb2+ in alkali activated slag binders. Cem Concr Res 32: 1971-1979.
11. Hills CD, Pollard SJT (1997) The influence of interference effects on the mechanical microstructural and fixation Characteristics of cement-solidified hazardous waste forms. J Hazard Mater 52: 171-191.
12. Wang S, Vipulanandan C (2000) Solidification/Stabilization of Cr (VI) with cement Leachability and XRD analysis. Cem Concr Res 30: 385-389.
13. Macias A, Kindness A, Glasser FP (1997) Impact of carbon dioxide on the immobilization potential of cemented wastes: Chromium. Cem Concr Res 27: 215-225.
14. U.S. Environmental Protection Agency (1986) Test Method for Evaluating Solid Wastes, SW-846, 3rd ed., Office of Solid Waste and Emergency Response, Washington DC.
15. Alunno Rosseti V, Medici F (1995) Inertization of toxic metals in cement matrices: effects on hydration and hardening. Cem Concr Res 25: 1147-1152.
16. Corner JR (1990) Chemical Fixation and Solidification of Hazardous wastes. Van Nostrand- Reinhold, New York.
17. Taylor HFW (1964) The Chemistry of Cement, Vol. (II) Academic press, New York.
18. Trezza MA, Ferraiuelo MF (2003) Hydration study of limestone blended cement in the presence of hazardous wastes containing Cr(VI). Cem Concr Res 33: 1039-1045.
19. Minocha AK, Jain N, Verma CL (2003) Effect of Inorganic Materials on the Solidification of Heavy metal Sludge. Cem Concr Res 33: 1695-1701.
20. Halim CE, Amal R, Beydaun D, Scott JA, Low G (2004) Implication of the structure of cementitious wastes containing Pb(II), Cd(II), As(V) and Cr(VI) on the leaching of metals. Cem Concr Res 34: 1093-1102.
21. Kolovas K, Tsivilis S, Kakali G (2002) The effect of foreign ions on the reactivity of the CaO-SiO2-Al2O3–Fe2O3 system Part (II): Cations. Cem Concr Res 32: 463-469.
22. Olmo IF, Chacon E, Irabien A (2001) Influence of Lead, Zinc, Fe(III) and Cr(III) oxide on the setting time and strength development of Portland cement. Cem Concr Res 31: 1213-1219.
23. Roy A, Eaton HC, Cartledge FK, Tittlebaum ME (1991) Solidification/ Stabilization of a Heavy metal sludge by a Portland cement/fly ash binding mixture. Hazardous waste and Hazardous materials 8: 33-41.