Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 03, March-2023

Influence of Reuse of Drinking Water Treatment Plants Sludge in Concrete

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***Abstract*— This investigation addresses the effect of sludge from water treatment plants as partially replacing cement on the mechanical properties. Various mixtures of sludge powder (SL) after heated treatment at 200℃, 300℃, and 500 ℃ are produced by partially replacing cement with 0%, 5%, 10%, 15%, 20%, and 25 wt%. SL after heated treatment at 200℃ with 0%, 5%, 10%, 15%, 20%, and 25 wt% was replaced with 10% liquid sodium silicate. The program includes the substitution of cement with 5% un-hydrated lime and 10% silica fume at sludge powder after heated treatment at 200℃ with 0%, 5%, 10%, 15%, 20%, and 25 wt%. A series of laboratory tests were performed to investigate the mechanization of strength development which included compressive strength, splitting tensile, flexural strength, SEM, EDX, and mapping. Generally, the results showed that using 5%, 10% sludge in concrete increased the strength and then decreased at 15-25% of sludge. The use of silica fume improved the strength the most and also increase heated treatment of Sludge increased the strength.**

Keywords— Drinking water treatment plant sludge; sodium silicate; Un-hydrated lime; silica fume

I. INTRODUCTION

The rapid population growth translates into increased demand for drinking water which results in water treatment plants are produced more drinking water than in the last decades [1]. Conventional processes for drinking water treatment involve coagulation-flocculation, sedimentation, and filtration, which produced more precipitates or wastes referred to term drinking water treatment sludge [2]. The process of coagulants for water purification is used chemical materials to separate the solid-liquid in the treatment process [3, 4]. The materials are used in the coagulant process as Aluminium salts (e.g., $Al_2(SO_4)_3.18H_2O$, Poly-aluminum chloride) or Fe salts (e.g., $FeCl_3.6H_2O$, $FeCl_2$, $FeSO_4.7H_2O$) [5, 6]. The disposal sludge method has become most common in landfills, which is more expensive, and is against environmental laws [1, 7]. Therefore, the efforts for the utilization of sludge strategies would supply a safe and sustainable solution to sludge [3]. THE development of strategies for sludge reconnoitered the potential of using sludge as an ingredient construction material in preparing concrete and mortar, instead of disposal in landfills [8]. The sludge has been applied as filler material to ceramic and bricks products [9-11]. Besides, the feasibility of applying sludge to produce lightweight aggregates [12, 13], sand substitute supplementary cementitious material containing organic matter and heavy metals as alumina-siliceous [14,15]. Authors reported that the use of sludge was treated at 105 ℃ for 2h [16, 17]. This treatment method was more friendly and environmentally and saved energy due to low-temperature requirements and no emission of greenhouse gas [2, 18]. However, most of the studies demonstrated the addition of sludge content could decrease the strength [19]. It is worth mentioning that sodium silicate, limestone powder, and silica fume improved the mechanical characteristics of concrete [20-22].This paper, therefore, aims to study the mechanical properties, scanning electron microscopy (SEM), energy dispersive X-ray (EDX), and mapping of concrete. This paper also aims to study the effect of using sludge after heated treatment at200℃, 300℃, and 500 ℃ as partially replacing cement with 0%, 5%, 10%, 15%, 20%, and 25 wt%. The influence of sodium silicate, un-hydrated lime and silica fume with a ratio of 10%, 5% and 10%, respectively, on using sludge after heated treatment at 200℃ as partially replacing cement with 0%, 5%, 10%, 15%, 20%, and 25 wt%.

II. MATERIALS

A. Ordinary Portland cement (OPC)

Cement was produced with CEM I 52.5N according to ASTM C150 by Misr Beni Suef Company (MBSC), Egypt. The specific gravity, fineness, and surface area of OPC were 3.15, 3500 Cm^2/g, and 3210 cm^2/g. The chemical properties of cement are in Table (1).

TABLE (1): THE CHEMICAL OXIDE ANALYSIS OF CEMENT, SLUDGE, LIME AND SILICA FUME BY XRF (WT %).

Oxide	SiO_2	Fe_2O_3	K_2O	Na_2O	CaO	Al_2O_3	TiO_2	MnO	P_2O_5	SO_3	MgO	CL	H_2O	LOI
Cement	20.55	3.62	0.23	0.52	60.95	5.35	-	-	-	2.81	1.03	0.08	-	-
sludge	42.4	10.97	0.73	0.54	4.91	14.57	1.21	0.45	0.72	2.75	1.61	0.24	-	18.62
lime	1.62	0.2	0.03	16	70.9	0.4	0.1	-	0.09	1.05	0.23	-	-	25.14
silica fume	96	1.44	1.2	0.46	1.2	1.1	-	-	-	0.23	0.18	-	0.87	-

B. Sludge (SL)

Sludge was obtained from the drinking and wastewater treatment plants in Egypt. SL was crushed into powders and was sieved through cement sieve #200. The specific gravity and surface area of SL were 2.22, and 756 Cm2/g. Sludge powder was heated treatment at various temperatures of 200°C, 300°C, and 500°C for 2 hours. The chemical compositions of sludge are in Table (1), according to ASTM C150.

C. Un-hydrated lime stone (LS)

The hydrated lime was obtained from a lime production plant in Cairo, Egypt. The specific gravity of lime was 2.24. The chemical compositions of lime are provided in Table (1).

D. Silica fume (SF)

Silica fume was supplied by Sika Egypt Company with a particle size was 0.1 µm. The specific weight of SF was 2.64. The Chemical oxide analysis of silica fume is in Table (1).

E. Sodium silicate solution (S.S)

Sodium Silicate (Na_2SiO_3) was bought in the liquid state. The chemical composition included 32% SiO_2, 16% Na_2O, and 62% H_2O.

F. Coarse aggregate

Coarse aggregate was basalt from the Eastern Desert of Egypt. According to ASTM C127, Basalt was 22.50 mm the nominal maximum size, 2.65 specific weights, 1.6 t/m^3 bulk density, and 1.8% absorption.

G. Fine aggregate

Fine aggregate was river sand. According to ASTM C128, it was 4.75 mm nominal maximum size, 2.65 specific weights, 1.85 t/m^3 bulk density, and 2.4 fineness modulus.

H. Water

The casting and curing process used freshwater.

III. MIX PROPORTIONS

A. Mix preparation

Table (2) presents the mix proportions. Six different mixtures in each phase were produced according to ECP 203.

1. Phase (1): The partial replacement cement with sludge after heat treatment at 200℃ at 0%, 5%, 10%, 15%, 20%, and 25 wt%.
2. Phase (2): The partial replacement cement with sludge after heat treatment at 200℃ at 0%, 5%, 10%, 15%, 20%, and 25 wt% with 10%sodium Silicate by weight of sludge as a replacemnt.
3. Phase (3): The partial replacement cement with sludge after heat treatment at 200℃ at 0%, 5%, 10%, 15%, 20%, and 25 wt% with 5% lime by weight as a replacement of cement.
4. Phase (4): The partial replacement cement with sludge after heat treatment at 200℃ at 0%, 5%, 10%, 15%, 20%, and 25 wt% with 10% silica fume by the weight as a replacement of cement.
5. Phase (5): The partial replacement cement with sludge after heat treatment at 300℃ at 0%, 5%, 10%, 15%, 20%, and 25 wt.%6.

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ISSN: 2278-0181
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Phase (6): The partial replacement cement with sludge after heat treatment at 500℃ at 0%, 5%, 10%, 15%, 20%, and 25 wt%. Fig.1. presents the flow chart of experimental work .

TALE (2): THE MIX PROPORTIONS.

Phase	Mix Type	Cement (kg/ m^3)	Sand (kg/m^3)	Basalt (kg/m^3)	Water (kg/m^3)	SL (kg/m^3)	S S (kg/m^3)	lime (kg/m^3)	S F (kg/m^3)
Control	**A0**	400	836.84	906.9	200	0	0	0	0
Phase (1) Sludge after heat treatment at 200℃	**A1**	380	829.80	906.9	200	20	0	0	0
	A2	360	822.77	906.9	200	40	0	0	0
	A3	340	815.70	906.9	200	60	0	0	0
	A4	320	808.65	906.9	200	80	0	0	0
	A5	300	801.60	906.9	200	100	0	0	0
Phase (2) Sludge after heat treatment at 200℃	**B1**	380	828.53	906.9	200	18	2	0	0
	B2	360	820.21	906.9	200	36	4	0	0
	B3	340	811.89	906.9	200	54	6	0	0
	B4	320	803.58	906.9	200	72	8	0	0
	B5	300	795.26	906.9	200	90	10	0	0
Phase (3) Sludge after heat treatment at 200℃	**C0**	380	830	906.9	200	0	0	20	0
	C1	360	822.96	906.9	200	20	0	20	0
	C2	340	815.91	906.9	200	40	0	20	0
	C3	320	808.86	906.9	200	60	0	20	0
	C4	300	801.81	906.9	200	80	0	20	0
	C5	280	794.76	906.9	200	100	0	20	0
Phase (4) Sludge after heat treatment at 200℃	**D0**	360	830.34	906.9	200	0	0	0	40
	D1	340	823.29	906.9	200	20	0	0	40
	D2	320	816.24	906.9	200	40	0	0	40
	D3	300	809.2	906.9	200	60	0	0	40
	D4	280	802.15	906.9	200	80	0	0	40
	D5	260	795.1	906.9	200	100	0	0	40
Phase (5) Sludge after heat treatment at 300℃	**E1**	380	829.8	906.9	200	20	0	0	0
	E2	360	822.77	906.9	200	40	0	0	0
	E3	340	815.7	906.9	200	60	0	0	0
	E4	320	808.65	906.9	200	80	0	0	0
	E5	300	801.6	906.9	200	100	0	0	0
Phase (6) Sludge after heat treatment at 500℃	**F1**	380	829.8	906.9	200	20	0	0	0
	F2	360	822.77	906.9	200	40	0	0	0
	F3	340	815.7	906.9	200	60	0	0	0
	F4	320	808.65	906.9	200	80	0	0	0
	F5	300	801.6	906.9	200	100	0	0	0

A. Mixing and casting procedures

Fig. 2. presents the mixing and casting procedures. Mixing was performed in the mixer concrete in the laboratory. First, basalt and sand were put inside the mixer and mixed for 120 sec. Then, Portland cement and sludge were mixed with the mixture for 120 sec. The supplementary materials such as sodium silicate solution or lime or silica fume were added to the mixture for 180 sec. Finally, the water was added to the mixture for 240 sec until became a completely homogeneous mixture. The mixes were cast in special molds and were removed from the molds 24 h after casting. The specimens were moved to a moist curing tank in the lab that meets the ASTM C511.

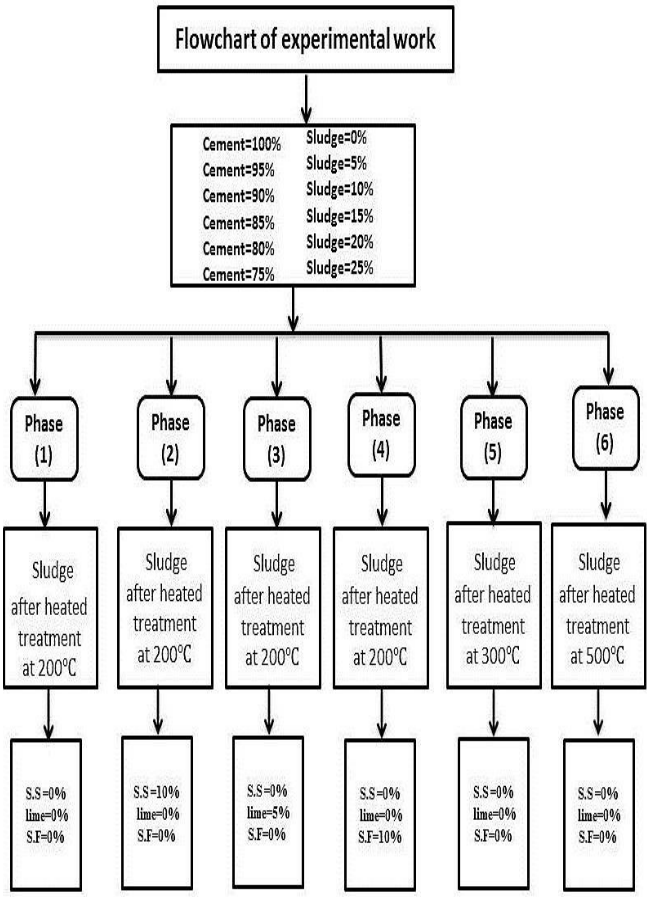

FIG.1: THE FLOW CHART OF EXPERIMENTAL WORK.

FIG. 2: THE MIXING AND CASTING PROCEDURES.

B. A. Experimental Procedure

All specimens were measured for compressive strength, splitting strength, and flexural strength. According to ASTM C39, The compressive strength was conducted with six cubes (0.1×0.1×0.1) m. According to ASTM C496, the split tensile strength was measured with three cylinders (0.1×0.2) m at 28 days. The two point load flexural strength test was performed at 28 days on three beams with (0.1×0.1×0.5) m. In addition to SEM, EDX, mapping for mixture of 10% SL after heat treated at 500°C, 10% sludge after heat treated at 200°C, 10% sludge after heat treated at 300°C and 10% sludge after heat treated at 200°C and 10% S.F.

IV. RESULTS AND DISCUSSION

A. Compressive strength

The compressive strength of sludge mixtures at 7 and 28 days is presented in Table (3) and Fig.3 (a) and (b). Overall, the compressive strength increases with an increase of sludge replacement up to 10% and then decreases with its increase up to 25% by weight. The compressive strength of samples containing 10% sludge after heated treatment 200°C was 330.21 kg/cm^2 compared with 302.02 kg/cm^2 for control at 28 days and the strength after curing for 7 days was more than that of the control. The increase in compressive strength is attributed to the formation of more hydrated products with curing ages, the accumulation of these hydrated products within the available pore spaces giving higher strength values

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ISSN: 2278-0181
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[14].5% and 10% sludge can act as a nucleating factor, which gives higher compressive strength at different curing ages; this is due to the formation of additional hydrated products such as that C–S–H and C-A-S-H created the reaction between liberated free portlandite, active silica Si+, and alumina-containing sludge. These hydrates improved compressive strength values [14]. The compressive strength of samples containing 10% sludge after heated treatment 300°C and 500 °C were 490.11 kg/cm^2 and 545.02 kg/cm^2 compared with 330.02 kg/cm^2 for 10% sludge after heated treatment 200°C. The results indicate that 5% and 10% sludge contents are the optimum replacement ratios in all phases. Thus, the results of compressive strength stated that the percentages of the sludge at 7 and 28 days mixed with 10% sodium silicate, 5% un-hydrated lime, and 10% silica fume improved compressive strength compared with that the percentages of the sludge after heated treatment at 200°C. The results introduced that 10% sodium silicate improved the compressive strength compared with the mixtures of 0% sodium silicate at 7 and 28 days. Hou et al. [23] stated that Silicate Sodium formed sodium aluminosilicate hydrate (N–A–S–H gel), which improved mechanical properties. For instance, 5% sludge after heated treatment at 200°C with 10% sodium silicate (B1) was increased by 11.76% compared with 5% sludge after heated treatment at 200°C with 0% sodium silicate (A1) at 28 days. The results also exhibited that the ratios of sludge after heated treatment at 200°C with 5% lime improved the strength relative to the mixtures of 0% lime. Besides, the lime powder contained CaO, SiO_2, Al_2O_3, MgO, and Fe_3O_4, thus, lime powder created Ca $(OH)_2$ and C–S–H gel, which is beneficial to the hydration of calcium silicates [24–27]. For instance, 10% sludge after heated treatment at 200°C with 5% lime (C2) was increased by 11.15% compared with 10% sludge after heated treatment at 200°C with 0% lime (A2), at 28 days. In addition, the results shown that the ratios of sludge after heated treatment at 200°C with 10% silica fume enhanced the strength relative to the mixtures of 0% silica fume. For instance, 10% sludge after heated treatment at 200°C with 10% silica fume (D2) was increased by 29.98% at 28 days compared with 10% sludge after heated treatment at 200°C with 0% silica fume (A2). On the other hand, the results exhibited an improvement in compressive strength for the percentages of the sludge mixed with 10% silica fume about their peer with 10% sodium silicate and 5% un-hydrated lime. Silica fume promotes the hydration of cement, which increases the amount of C–S–H gel, thus improving the microstructure of pastes [29-31]. SF enhanced compressive strength due to the smaller size of SF particles than cement, which is 0.1–0.5 nm [32-32]. Thus, SF can fill the void between cement grains, leading to micro-filling which increases of compressive strength.

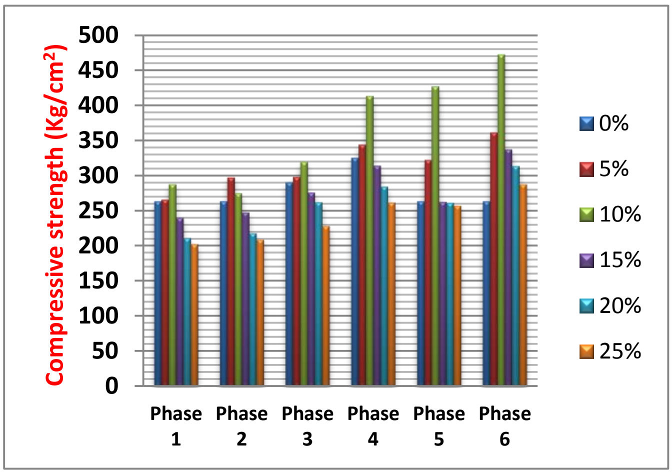

FIG.3 (A): COMPRESSIVE STRENGTH AT 7 DAYS.

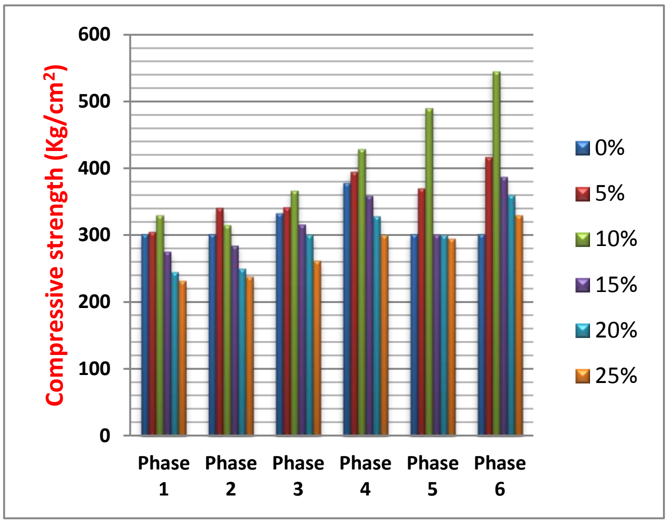

FIG.3.(B): COMPRESSIVE STRENGTH AT 28 DAYS.

B. Splitting tensile strength.

The splitting tensile strength of sludge mixtures at 28 days is presented in Table (3) and Fig.4. Obviously, the split tensile strength increases at 5% and 10% sludge and decreases with the increase of sludge up to 15–25% by weight. On the other hand, the results exhibited an improvement in split tensile strength for the percentages of the sludge mixed with 10% silica fume about their peer with 10% sodium silicate and 5% lime. For instance, 5% sludge after heated treatment at 200°C with 10% SS (B1) was increased by 11.14% compared with 5% sludge after heated treatment at 200°C (A1) and 10% sludge after heated treatment at 200°C with 5% lime (C2) and 10% SF (D2) was increased by 11.24% and 30%, respectively, compared with 10% sludge after heated treatment at 200°C (A2). The results exhibited an improvement in split tensile strength for the percentages of the sludge after heated treatment at 300°C and 500°C about their peer with the sludge after heated treatment at 200°C. For instance, 10% sludge after heated treatment at 300°C (E2) and 500°C (F2) was increased by 48.52%, and 51.11%, respectively, compared with 10% sludge after heated treatment at 200°C (A2).

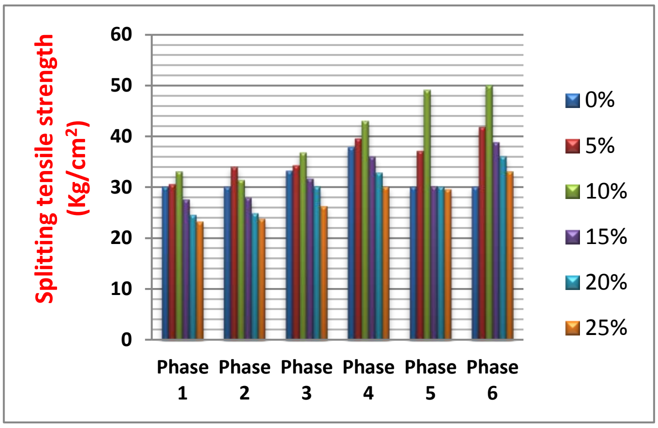

FIG.4: SPLITTING TENSILE STRENGTH AT 28 DAYS.

C. Flexural strength.

Table.3 and Fig.5 show the flexural strength of sludge mixtures at 28 days. It was known that the Flexural strength increases at 5% and 10% sludge and decreases with the increase of sludge up to 15–25% by weight. The results showed that the flexural strength was improved by 5, 10, 15, 20 and 25% sludge at 200°C with 10% silica fume about their peer with 10% sodium silicate and 5% lime. For instance, 5% sludge after heated treatment at 200°C with 10% SS (B1) was increased by 10.69% compared with 5% sludge after heated treatment at 200°C (A1) and 10% sludge after heated treatment at 200°C with 5% lime (C2), and 10% SF (D2) was increased by 11.21% and 29.99%, respectively, compared with 10% sludge after heated treatment at 200°C (A2) . On other hands, the results of flexural strength for the percentages of the sludge after heated treatment at 300°C and 500°C were improved compared with the percentages of the sludge at 200°C. For instance, 10% sludge after heated treatment at 300°C (E2) and 500°C (F2) was increased by 36.04%, and 54.34%, respectively, compared with 10% sludge after heated treatment at 200°C (A2).

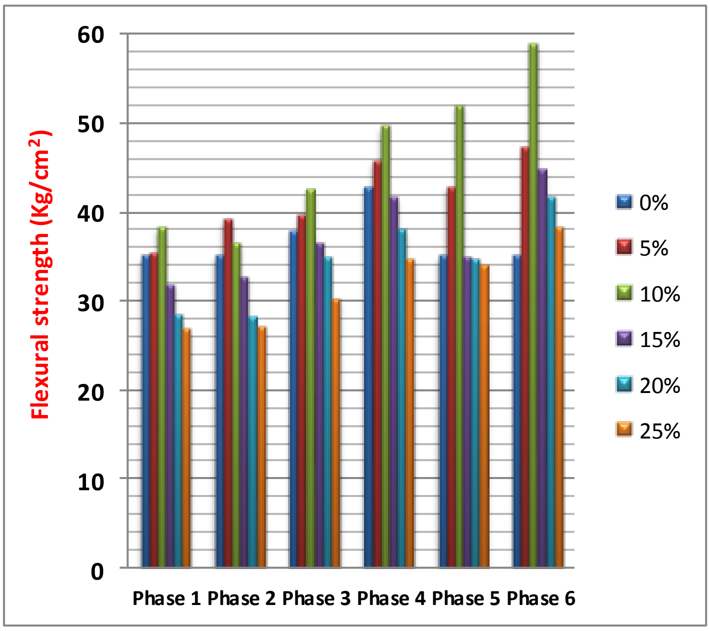

FIG.5: FLEXURAL STRENGTH AT 28 DAYS.

D. SEM& EDX& Mapping

The specified specimens of micrographs A2 (10% sludge after heat treated at 200°C), F2 (10% sludge after heat treated at 500°C), E2 (10% sludge after heat treated at 300°C), and D2 (10% sludge after heat treated at 200°C and 10% S.F) at 28 days by ZEISS apparatus for SEM, EDX, and mapping. Fig.6 exhibits large amounts of C-S-H and C-H gels that revealed homogeneity and bond strength. Fig. 6 (a) reveals the reason reduce of strength with increasing in the sludge ratios due to the presence of unreacted sludge at 10% sludge. In Fig.6 (b) presents the inner product (IP) that C-(A)-S-H gel. Fig.6 (c) exhibits large amounts of C-S-H gels that referred to the strong reaction between 10% sludge and SF. Fig.6 (d) and (e) shows that sludge after heat treatment at 500°C has hydration products(C-S-H) more than sludge after heat treatment at 300°C, as shown in Fig.6 (f). The chemical analysis of EDS and mapping present large amounts of the main elements Ca,

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Si, and Al in the binder matrix, as shown in Fig.7,8 and Table (4) .

TABLE (3): THE RESULTS OF COMPRESSIVE STRENGTH, SPLITTING TENSILE STRENGTH, AND FLEXURAL TENSILE STRENGTH.

Phase	Mix Type	Compressive strength at 7 days (Kg/cm^2)	Compressive strength at 28 days (Kg/cm^2)	Splitting tensile strength at 28 days (Kg/cm^2)	Flexural tensile strength at 28 days (Kg/cm^2)
Control	**Cont..**	263.06	302.02	30.1	35.1
Phase (1) Sludge after heat treatment at 200°C	**A1**	265.6	305.31	30.6	35.34
	A2	287.4	330.21	33.1	38.24
	A3	239.5	275.45	27.6	31.87
	A4	210.71	245.03	24.6	28.39
	A5	202.13	231.91	23.3	26.88
Phase (2) Sludge after heat treatment at 200°C	**B1**	297.13	341.23	34.01	39.12
	B2	274.6	315.32	31.42	36.54
	B3	247.32	284.55	27.99	32.82
	B4	217.58	250.12	24.92	28.21
	B5	208.86	238.42	23.85	27.11
Phase (3) Sludge after heat treatment at 200°C	**C0**	290.21	333.06	33.24	37.9
	C1	297.81	342.21	34.31	39.63
	C2	319.35	367.05	36.82	42.53
	C3	275.35	316.11	31.70	36.62
	C4	262.13	301.02	30.19	34.88
	C5	228.12	262.21	26.29	30.36
Phase (4) Sludge after heat treatment at 200°C	**D0**	325.36	378.35	37.92	42.88
	D1	343.91	395.11	39.63	45.77
	D2	413.21	429.21	43.04	49.71
	D3	313.62	359.22	36.01	41.6
	D4	284.12	328.54	32.9	38.01
	D5	261.23	300.41	30.09	34.76
Phase (5) Sludge after heat treatment at 300°C	**E1**	322.21	370.10	37.12	42.88
	E2	426.71	490.11	49.16	52.02
	E3	262.23	301.01	30.19	34.88
	E4	261.2	300.41	30.09	34.76
	E5	256.9	295.01	29.59	34.18
Phase (6) Sludge after heat treatment at 500°C	**F1**	361.35	417.11	41.83	47.3
	F2	472.13	545.02	50.02	59.02
	F3	337.21	387.22	38.82	44.85
	F4	313.35	360.21	36.11	41.72
	F5	287.38	330.15	33.10	38.24

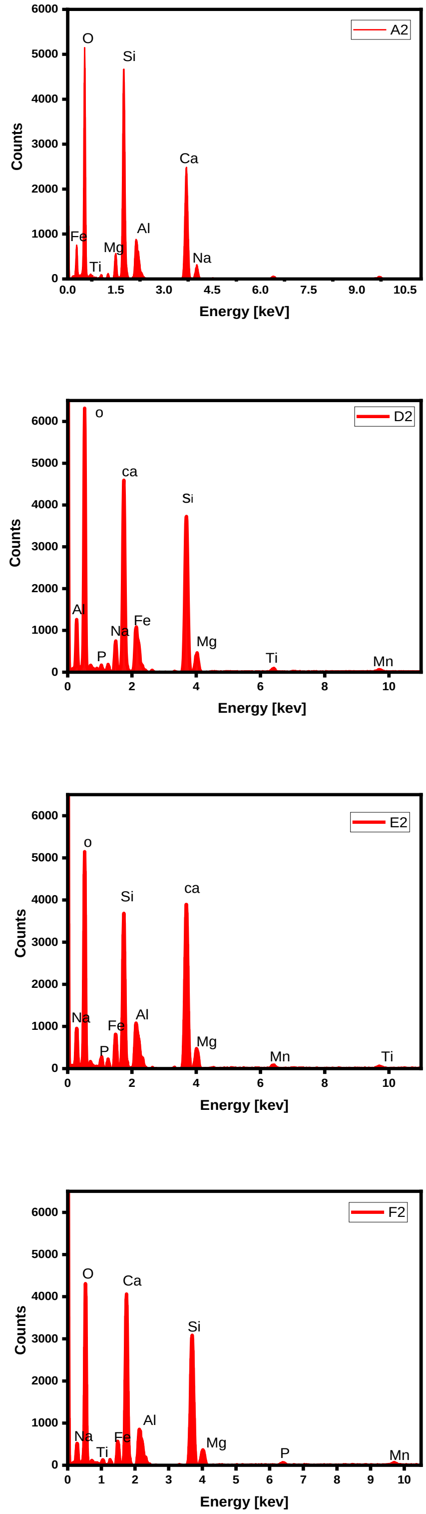

FIG. 7: EDS [A2 (10% SLUDGE AFTER HEAT TREATED AT 200°C),(2) D2 (10% SLUDGE AFTER HEAT TREATED AT 200°C AND 10% S.F,(3) E2 (10% SLUDGE AFTER HEAT TREATED AT 300°C),(4) F2 (10% SLUDGE AFTER HEAT TREATED AT 500°C)].

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TABLE (4) :EDS OF SPECIMENS MATRIX.

Element	A2		D2		E2		F2	
	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %	Weight %	Atomic %
Oxygen	41.01	59.65	23.80	40.67	37.25	56.79	38.78	58.02
Aluminium	2.52	2.17	3.17	3.21	2.99	2.71	2.43	2.16
Silicon	21.53	17.84	21.07	20.51	14.21	12.34	17.42	14.84
Calcium	30.33	17.61	46.09	31.44	39.32	23.93	36.56	21.83
Sodium	0.63	0.64	1.06	1.26	1.54	1.63	1.01	1.05
Iron	2.70	1.12	3.38	1.65	3.08	1.34	2.55	1.09
Titanium	0.41	0.20	0.23	0.13	0.27	0.14	0.31	0.16
Magnesium	0.67	0.64	0.76	0.86	0.84	0.84	0.73	0.72
Potassium	0.21	0.13	0.23	0.16	0.31	0.19	0.18	0.11
Manganese	0.00	0.00	0.21	0.10	0.20	0.09	0.03	0.01

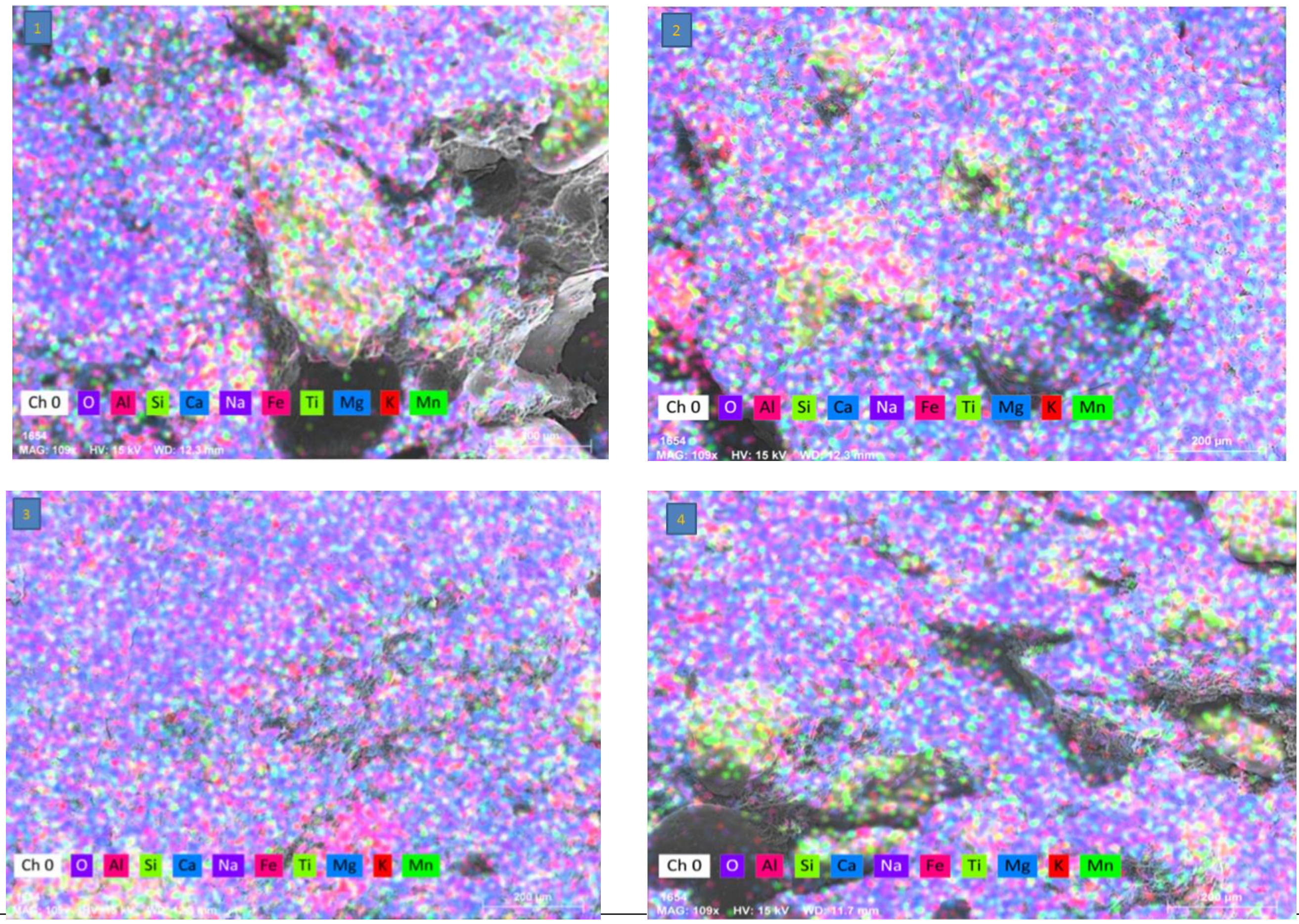

FIG. 8: MAPPING [(1) A2 (10% SLUDGE AFTER HEAT TREATED AT 200°C),(2) D2 (10% SLUDGE AFTER HEAT TREATED AT 200°C AND 10% S.F,(3) E2 (10% SLUDGE AFTER HEAT TREATED AT 300°C),(4) F2 (10% SLUDGE AFTER HEAT TREATED AT 500°C)].

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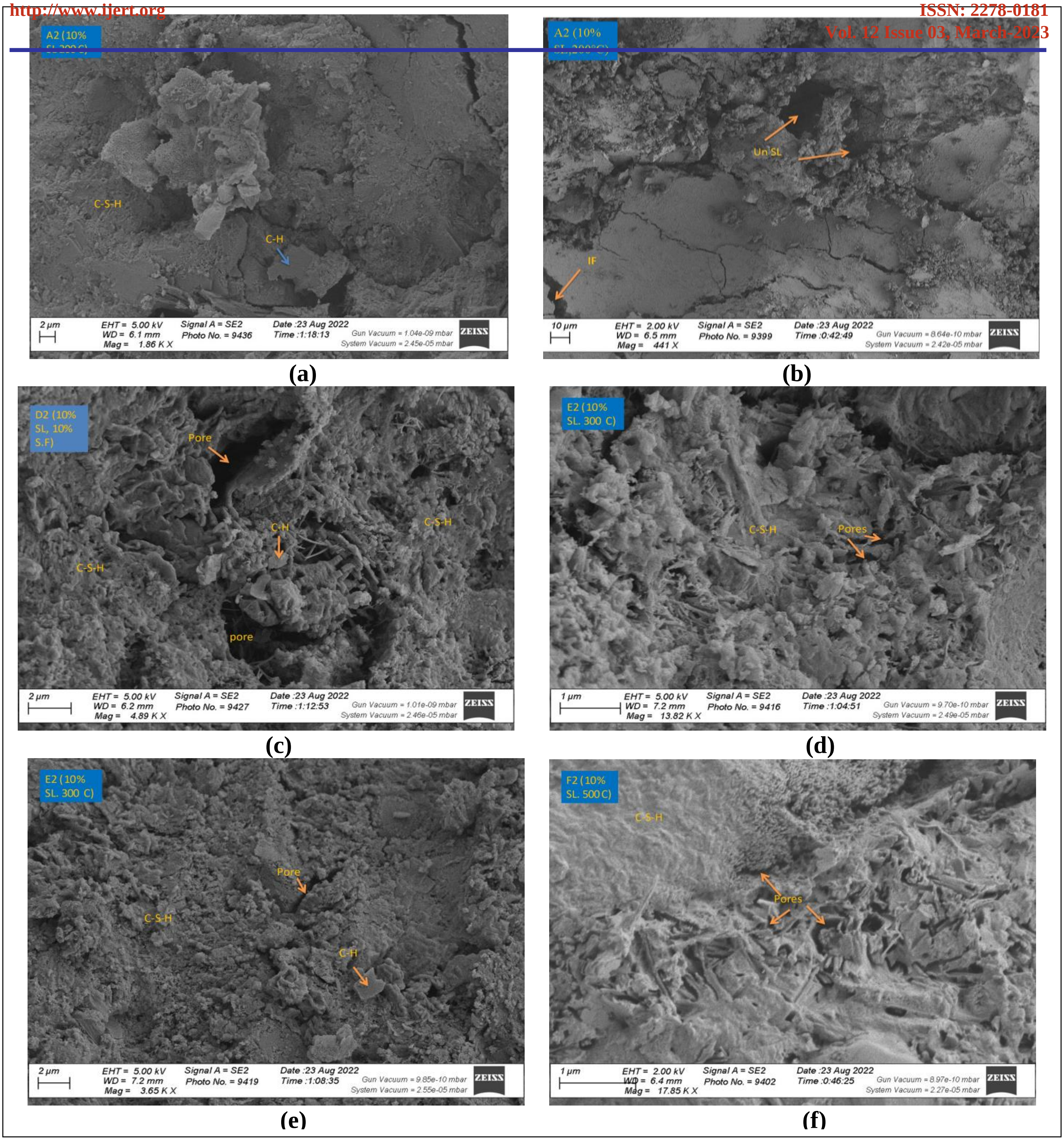

FIG. 6: SEM[(A,B): A2 (10% SLUDGE AFTER HEAT TREATED AT 200°C),(C): D2 (10% SLUDGE AFTER HEAT), (D,E): E2 (10% SLUDGE AFTER HEAT TREATED AT 300°C),(F): F2 (10% SLUDGE AFTER HEAT TREATED AT 500°C)].

V. Conclusion

The mechanical properties, SEM, EDX, and mapping were studied for drinking water treatment plant sludge powder after heated treatment at 200℃, 300℃, and 500 ℃ were partially replaced cement with 0%, 5%, 10%, 15%, 20%, and 25 wt%. SL after heated treatment at 200℃ with 0%, 5%, 10%, 15%, 20%, and 25 wt% was also replaced with 10% liquid sodium silicate. In addition, the substitution of cement with 5% un-hydrated lime and 10% silica fume at Sludge powder after heated treatment at 200℃ with 0%, 5%, 10%, 15%, 20%, and 25 wt%. The results can be concluded that:

1. Sludge is a Pozzolanic material can be used as partial replacement of cement.

2. The compressive, tensile, and flexural strength of concrete is improved by the incorporation of 5 % Sludge powder after heat treatment at 200℃ and replaced with 10% SS. As sludge powder increases up to 5% by weight, then the strength decreases.

3. The incorporation of 5% un-hydrated lime or 10% silica fume with sludge powder after heat treatment at 200℃ can let the development of mechanical properties. However, with the increase in SL powder at 10%, the mechanical properties are increased, but up to 10% SL powder by weight, the strength decreases.

4. The treatment of SL powder with increased heat has a positive effect on its strength. The treatment of SL powder at 500℃ improved the strength compared with SL powder after heating at 200 ℃ and 300℃. However, 10 % SL powder after heated treatment at 500℃ increased by 80% the strength compared with 0%SL powder and the strength decreased with the increase of sludge up to 10–25% by weight.

5. The microstructure analysis revealed that 10% SL after heat treatment at 500°C tends to have a higher hardness.

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