Uncorrected Proof

Check for updates

Effect of sewage sludge and rock dust on strength and workability of concrete

Elham Khalilzadeh Shirazi, Mostafa Khezri, Reza Marandi and Mahmoud Shariat

Withdrawn

ABSTRACT

The production of sewage sludge originating from municipal wastewater treatment plants has [illegible] increased significantly. Sludge is considered the largest byproduct of wastewater in volume, whos[illegible] process and disposal is considered one of the most complex environmental problem[illegible]per reports experimental findings regarding the feasibility of using sewage sludge in c[illegible]ete a[illegible] alternative to freshwater varying from 0 to 100% by weight. The concrete samples [illegible]e stu[illegible]d w[illegible] regard to compressive strength and workability. The results showed that s[illegible]e can be [illegible]aced [illegible] to 50% by weight of water without any significant deterioration of me[illegible]al properti[illegible] reinforce concrete strength, rock dust was added to co[illegible] as an a[illegible]e to the whole fine aggregates. According to the findings, the presence of rock [illegible]as bene[illegible]ffects on compressive strength, whose samples with 50% sludge we[illegible]tively b[illegible] terms of compressive strength than the normal concretes. Furth[illegible]re, the [illegible] of rock dust on concrete workability was negligible. In addition to environmental [illegible]servation, t[illegible]f both sewage sludge and rock dust in concrete could save a large amount of [illegible]water an[illegible]revent further depletion of natural aggregates respectively. Moreover [illegible] a mea[illegible] disposal and resource recovery.

Key words | compressive strength, [illegible]e, rock d[illegible]age sludge, workability

E[illegible]halilza[illegible]i (corresponding [illegible])
[illegible]ezri
[illegible]ariat
Dep[illegible] Environment and Energy, Science and [illegible]esearch Branch,
Islamic Azad University,
Tehran,
[illegible]an
E-mail: *elham_khalilzadeh62@yahoo.com*

Reza Marandi
Department of Environmental Engineering,
Islamic Azad University,
North Tehran Branch,
Tehran,
Iran

INTRODUC[illegible]N

Curre[illegible] accor[illegible] scien[illegible]phasis on environmental [illegible]h and [illegible] pollution issues, there is an [illegible]reasing [illegible]eness of [illegible]icial and safe wastewater dis[illegible]. Prope[illegible] of sewage sludge and its byproducts [illegible]iga[illegible] of environmental problems (Oakes [illegible]. Appro[illegible]99% of initial wastewater stream in wa[illegible]ater treatment plants is discharged as treated water [illegible] remainder is a dilute suspension of solids, com[illegible]wn as sludge (Barrera-Díaza *et al.* 2011). Sludge is an [illegible]vitable byproduct of wastewater treatment processes which is generally generated at a rate of 70–90 g/person equivalent per day (Pescod 1992; Tamrabet *et al.* 2009; Tamrabet). The presence of pollutants and unstable pathogen which leads to potential health and environmental hazards is a matter of crucial importance (Mohammad & Athamneh 2004; Ahmad *et al.* 2006). The most widely used final disposal method of sludge is discharge into landfills, which is considered detrimental to the soil and urban landscape (Hoffman 2000).

The ideas of using sludge as a component of cement (Onaka 2000; Taruya *et al.* 2002), in making building blocks and panels, in the paper and pulp industry (Zelic 2005), in the creation of hempcrete combined with cellulose fibers in the cement matrix, are considered useful methods of sludge disposal (Eires & Jalali 2005). Incinerator sewage sludge ash with pozzolanic properties which is submitted to acid washing, has the potential to be used in construction products as well (Shahul Hameed & Sekar 2009; Donatello

doi: 10.2166/wrd.2014.031

Downloaded from http://iwaponline.com/jwrd/article-pdf/doi/10.2166/wrd.2014.031/221064/jwrd2014031.pdf
by guest

Uncorrected Proof

et al. 2010). Using pulverized sludge ash as a partial replacement for cement and reclaimed wastewater as mixing water for concrete could be regarded as a means of waste disposal and resource recovery (Joo 1989; Joo & Kuan 1994; Valls et al. 2004; Yagüe et al. 2005; Noruzman et al. 2012; Lina et al. 2012). Physical and mechanical properties and durability of concrete with added dry sewage sludge that have been studied concluded that up to 10% of treatment plant sludge can be added to concrete for specific uses and in some cases for low-strength mass concrete that could be used for bases and sub-bases of roads with light traffic, as a filler, etc. (Mohammad & Athamneh 2004; Malliou et al. 2007; Mun 2007). In some cases, processed wastewater sludge can be used to improve the mechanical properties of concrete. Moreover, the presence of sludge in concrete with using coagulants or treating electrochemical treatment method has beneficial effects on the long-term properties (Barrera-Díaza et al. 2011).

On the other hand, the production of concrete requires a large amount of water and only freshwater is used in most of its production. In fact, approximately 800 and 825 billion liters of water were used in the production of concrete during the years 1997 and 2010 respectively, at an average of 250 kg of cement per 1 m^3 of concrete [illegible] water/cement ratio (Aïtcin 2000). While [illegible] is regarded as a country with little precipitation and [illegible] demand for [illegible] is on the increase day by day ([illegible] et al. [illegible]), 80 million cubic meters of concrete with average cement grade of 250 kg per m^3 is produced [illegible] 11,000 million cubic meters of water annually. Therefore [illegible] alternatives for concrete mixing water is necessary due to the higher consumption of [illegible] water [illegible] by global population growth and industrialization.

[illegible] presence of sludge impurities in mixing water [illegible] concrete [illegible] affect its strength and durability (Lee et al. 2001); thus crushed rock dust was chosen as an alternative to fine aggregates to evaluate the possibility of its use [illegible] these properties.

The available sources of natural sand are becoming depleted due to excessive extraction of natural aggregates for using in construction industry (Nagabhushana & Sharada bai 2011). The continued use of river sand in concrete poses serious problems with respect to its availability, cost and environmental impact (Ilangovana et al. 2008). Hence, some investigations have been carried out to eliminate the aforementioned concerns and evaluate the effect of rock dust on mechanical properties of concretes.

With respect to the use of quarry rock dust in concrete as an alternative to fine aggregates, Sahu et al. (2003) reported a significant increase in compressive strength, modulus of rupture and split tensile strength [illegible] 40% [illegible] replaced with Quarry Rock Dust. Ilangovan & Nagarajan (2006) concluded that the full replacement of natural sand with quarry rock dust is possible with proper treatment of quarry dust before utilization.

Based on two other researches, [illegible] found out that the compressive, flexural [illegible] and durability studies of concrete made of quarry rock dust [illegible] nearly 10 and 14% more than the conventional concrete respectively (Ilangovana et al. 2008; Ismail Haneef & Sekar 2009). Stone Crusher dust could be an effective alternative to fine aggregates in paving blocks [illegible] 50% (Nanda Radhikesh et al. 2010), and in mortars and concrete up to 40%, with negligible effects on mechanical properties (Nagabhushana & Sharada bai 2011).

Several efforts have been made to use composites of water and wastewater treatment sludge with different types of wastes. Mechanical properties of concretes produced with a composite of water treatment sludge and sawdust characterized it as a lightweight non-structural concrete (Sales et al. 2010, 2011). The joint addition of water treatment sludge and recycled concrete rubble aggregates has been proven to be a feasible recycling alternative from the viewpoint of axial compression strength, modulus of elasticity, water absorption and tensile strength (Sales & Rodrigues de Souza 2009). In development of lightweight aggregate using dry sewage sludge, coal ash could be used to improve compressive strength and sintering temperature due to high contents of SiO_2 and Al_2O_3 (Wanga et al. 2009).

The objective of this research was to study the mechanical properties of concrete produced with a composite based on sewage sludge and rock dust, instead of water and fine aggregates respectively. The use of this composite may offer a good alternative to the recycling of sewage sludge and rock powder, contributing to the reduction of environmental impacts caused by sludge discharge into the environment, depletion of natural sand in order to be used as fine aggregates and economical aspect of consuming sludge instead of freshwater in concretes.

Withdrawn

Downloaded from http://iwaponline.com/jwrd/article-pdf/doi/10.2166/wrd.2014.031/221064/jwrd2014031.pdf
by guest

Uncorrected Proof

MATERIALS AND METHODS

Cement

Ordinary Portland cement II was used throughout. Table 1 presents the chemical compositions and physical properties of the cement.

Aggregates

The aggregates used include crushed granite stones and naturally occurring river-washed quartz sand which were well-graded by means of 12.5, 19.25, 9.5 and 4.75 mm sieves and 9.5, 4.75, 2.36, 1.18, 0.6, 0.3 and 0.15 mm sieves respectively, according to ASTM C136-06 (ASTM 1996). Physical aggregate properties are given in Table 2.

Table 1 | Chemical composition and physical properties of the cement

Chemical properties	Av[illegible] valu[illegible]
Specific gravity	[illegible]
Initial setting	3[illegible]
Normal consistency	0/2[illegible]
SiO_2	[illegible]2/05
Al_2O_3	[illegible]
Fe_2O_3	3/[illegible]
CaO	62/18
MgO	2/18
SO_3	1/96
Na_2O	0/47
K_2O	0/5
[illegible]ss on igni[illegible]	3/41
[illegible]	4/51
[illegible]F	10/93

[illegible]cal aggregate properties

Property	Sand
Specific gravity	2.725
Bulk density (Kg/m^3)	1,912
Absorption (%)	0.272
Fine particles < 0.063 mm (%)	9

Figures 1 and 2 show the particle size distribution of coarse and fine aggregates.

Rock dust

Exporting white rock dust with fin[illegible]ss m[illegible] of 2.80 is used in this study. Figure 3 shows p[illegible]cle siz[illegible]ibution of rock dust.

Sources and analys[illegible] of se[illegible]e s[illegible]mples

The sludge us[illegible] in the dev[illegible] and production of the concretes [illegible]d from Gh[illegible]s wastewater treatment plant in [illegible]hran [illegible]eatment plant, with a treatment

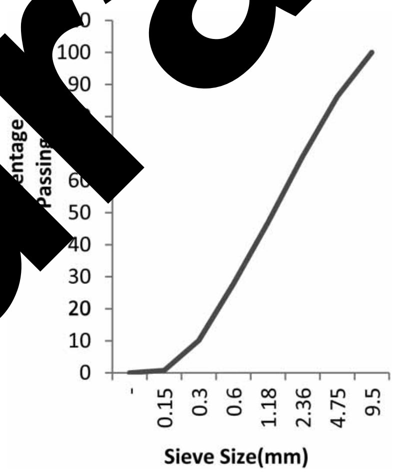

Figure 1 | Particle size distribution for fine aggregates.

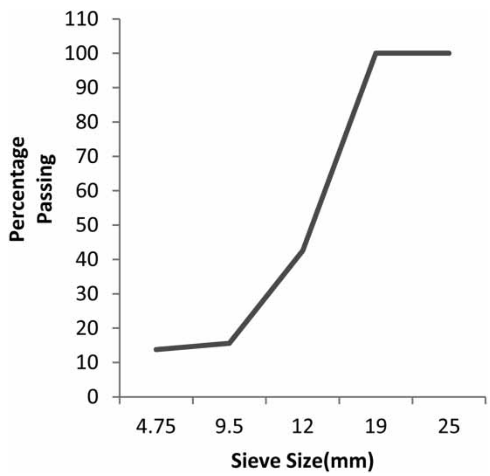

Figure 2 | Particle size distribution for Coarse aggregates.

Downloaded from http://iwaponline.com/jwrd/article-pdf/doi/10.2166/wrd.2014.031/221064/jwrd2014031.pdf
by guest

Uncorrected Proof

Withdrawn

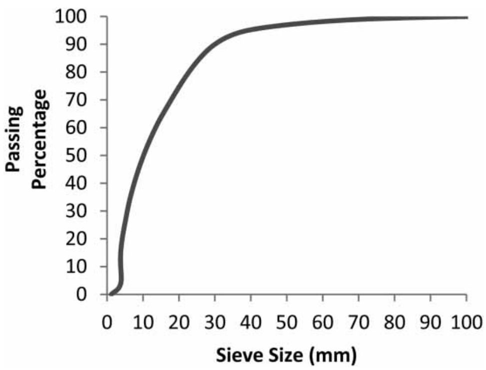

Figure 3 | Particle size distribution for rock dust.

capacity of 85,000 people, is located in the west of Tehran, with an area of 13 hectares. It has been in operation since 2008. The treatment method of this plant is the activated sludge. The total amount of excess sludge in ordinary (days without rain) and in maximum conditions (rai[illegible] days) is 247 and 502 m^3/day respectively.

'Municipal Sewage Sludge Management Plan' carried out by Torabian & Moumeni (2003), a case study on Sha[illegible] Qods Treatment Plant, was used which studied ph[illegible]al, chemical and biological properties of the sludge [41].

The samples were collected in plastic contai[illegible] lime was added to each container t[illegible]tain a [illegible] more, 24 hours before being used in [illegible] to el[illegible] a majority of microorganisms. Sludge s[illegible] were sub[illegible] to chemical analysis using [illegible]esen[illegible] Table 3.

Concrete mix de[illegible]

For preparing [illegible]crete sp[illegible]ens, wast[illegible]ter sludge, potable w[illegible]ter, Portl[illegible]ement ||, [illegible]nd coarse aggregates and r[illegible]ere us[illegible]or each c[illegible] meter of concrete, concre[illegible]iven as shown in Table 4. Four differ[illegible]eries [illegible] specimens were prepared; C-C, [illegible]RD, [illegible]nd C-RD[illegible]C-C means 'Controlled Concrete', [illegible]re[illegible]d to concrete with 'Sludge'. RD stands for rock [illegible] C-RD-S means concrete containing rock dust and s[illegible]e.

Water/cement ratio and cement grade were fixed at 0.45 and 350 kg/m^3 respectively. Aggregates were graded with sieve series before being used in concretes.

Different percentages (25, 50, 75 and 100%) of sewage sludge replaced water to measure 7, 28 and 90-day

Table 3 | Elemental composition of the sludge

Element	[illegible]
Ca	[illegible]0.37
Si	14.13
Fe	[illegible].13
P	[illegible]
Al	4.[illegible]
Mg	1.86
K	1.22
Ti	0.899
Na	0.729
S	0.424
Zn	0.265
Cl	0.224
Sr	0.148
Mn	0.130
Cu	0.0758
[illegible]a	0.0357
[illegible]	0.0229
C[illegible]	2.86

[illegible]ressive strength. Concrete compression in molds was [illegible]rformed by a vibration table (Neville 2005).

Curing of specimens

Casted specimens were left for a day in mold in a humid laboratory condition (23 ± 2°C). Then, they were removed and immersed in water for 7, 28 and 90 days.

All blocks were prepared and maintained in the same conditions. In other words, parameters such as concrete compression, mixture rate, temperature, humidity, cement type and grading of coarse and fine aggregates in all tests were considered fixed (Leung *et al.* 2003). Samples were placed in a humid environment for 24 hours. Therewith, all concrete cubes were maintained in potable water for different durations (7, 28 and 90 days) to cure.

Compressive strength and workability tests

The slump of fresh concretes was measured according to ASTM C143-90a (1998) and the compressive strength of

Downloaded from http://iwaponline.com/jwrd/article-pdf/doi/10.2166/wrd.2014.031/221064/jwrd2014031.pdf by guest

Uncorrected Proof

Withdrawn

Table 4 | Mixture proportions of the concrete (kg/m^3)

Samples	Cement (kg)	Water (L)	Fine aggregate (kg)	Coarse aggregate (kg)	Sludge (kg)	Rock dust (kg)	Additive [illegible]180) (kg)
C-C	350	157.5	1,135.5	757	–	–	1.05
C-RD	350	157.5	–	757	–	1,135.5	[illegible]
C-S25	350	118.125	1,135.5	757	39.375	–	[illegible]
C-S50	350	78.75	1,135.5	757	78.75	–	1.05
C-S75	350	39.375	1,135.5	757	118.125	[illegible]	[illegible]
C-S100	350	157.5	1,135.5	757	157.5	[illegible]	[illegible]
C-RD-S25	350	39.375	–	757	39.375	[illegible]	[illegible]
C-RD-S50	350	78.75	–	757	78.75	[illegible]	[illegible]
C-RD-S75	350	118.125	–	757	118.125	[illegible]	1.05
C-RD-S100	350	157.5	–	757	[illegible]	[illegible]	1.05

samples was determined based on ASTM C109-99 (1999). In all curing times, two samples were tested for co[illegible]sive strength and their average value was obtained as co[illegible]sive strength.

A compressive strength test was carried ou[illegible] determine the ultimate strength that causes concret[illegible] fail in compression. Concrete cube specimens that [illegible]been cured for 7, 28 and 90 day[illegible]were te[illegible] comp[illegible] strength. The specimens [illegible]em[illegible]ed [illegible]he curing tank and allowed to dry, after [illegible]hey were[illegible]d in a compression machi[illegible] an[illegible] a [illegible]ressive lo[illegible] was applied until failure. T[illegible]at failure[illegible]sed to compute the compr[illegible] str[illegible] shown [illegible]he following equation[illegible]

(Compre[illegible]strength[illegible]ilure load (N)/ [illegible]ube cro[illegible]tional ar[illegible]m^2))

[illegible]carry[illegible]ump test, a slump cone placed on a h[illegible] flat sla[illegible]filled with fresh concrete in four lay[illegible]ach layer being tamped 25 times with a tamping [illegible] excess concrete beyond the cone top was re[illegible]nd the surface smoothed using a trowel. The cone was vertically pulled from the mold concrete and placed beside the slumped concrete. A tamping rod was placed horizontally on the top of slump cone and a ruler was used to measure the concrete slump (ASTM 1998).

R[illegible]ULTS A[illegible]USSION

S[illegible]analysis

[illegible]rious alternatives of Qods' sludge disposal can be studied. [illegible]irst option is burning which is not suitable due to sev[illegible]ral reasons such as the air pollution of Tehran and the high cost of constructing and maintaining incinerators (Abbaspour & Soltaninejad 2004; Fytili & Zabaniotou 2006; Kanitha *et al.* 2014).

The alternative of sludge disposal with wastes to landfills cannot be considered due to the high volumes of municipal waste produced in Tehran, as well as the great expense of transportation.

The third option, composting, could not be applied from the view point of economy, inefficient management and the increasing trend of air pollution. Therefore, finding a feasible alternative to environmentally proper disposal of sludge is necessary.

According to the results of 'Municipal Sewage Sludge Management Plan' (Torabian & Moumeni 2003), based on US EPA standards and regulations, the resulting sludge holds the qualities of class B pathogenically. It indicates that stabilization of sewage sludge is not implemented well in this treatment plant. Consequently, the application of sludge in concrete with adding some lime to kill microorganisms will be an advantageous option for sludge disposal to the environment.

Downloaded from http://iwaponline.com/jwrd/article-pdf/doi/10.2166/wrd.2014.031/221064/jwrd2014031.pdf
by guest

Uncorrected Proof

Withdrawn

Because of the physical–chemical processes that are involved in activated wastewater sludge treatment, sludge tends to accumulate heavy metals existing in the wastewater. Concentration of heavy metals in sewage sludge may vary widely, depending on the sludge origins (Fytili & Zabaniotou 2006). Regarding the values of heavy metals studied in the present research and the aforementioned plan, it bears an exceptionally excellent quality. The main reason for the low level of heavy metals in sludge samples can be related to the absence of industrial units in the vicinity of Qods treatment plant. Subsequently, the usage of sludge in concrete could be environmentally practicable regarding the potential leakage of heavy metals from concrete (Torabian & Moumeni 2003). In addition, an insignificant amount of heavy metals leakage from concretes containing municipal wastewat[illegible] which has been studied specifically by other re[illegible]archer[illegible] can be attributed to the slow and gradual d[illegible] process. Moreover, the immobilization effect of [illegible]emen[illegible] heavy metals should be taken into account (K[illegible]lzadeh [illegible]r-andi 2012).

Workability

Figure 4 presents th[illegible] slump tes[illegible] The values were within the ran[illegible]m and tota[illegible] trends seem to be on the decrea[illegible]n ge[illegible] presence of sludge solid particles in [illegible] m[illegible]xing [illegible]ter fo[illegible]crete was observed to have an infl[illegible]ce on sl[illegible] (Ch[illegible]eera & Lertwattanaruk 2009). Th[illegible]mum decli[illegible]re observed in concretes with 25 and 5[illegible]dge which were almost equal to the referenced [illegible]mples. [illegible] obtained from sludge and rock dust yielded [illegible] value[illegible]ompared with samples containing only sev[illegible]ludge in all different percentages. However, this redu[illegible] is negligible.

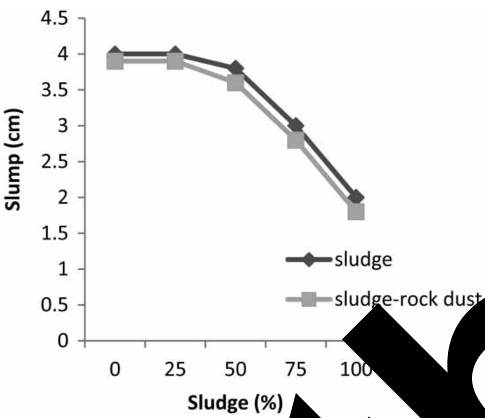

Figure 4 | Slump varied according to [illegible]ent.

[illegible]ompressive strength

The compressive strength values of the concretes are presented in Figure 5 for 7, 28 and 90 days. The values for

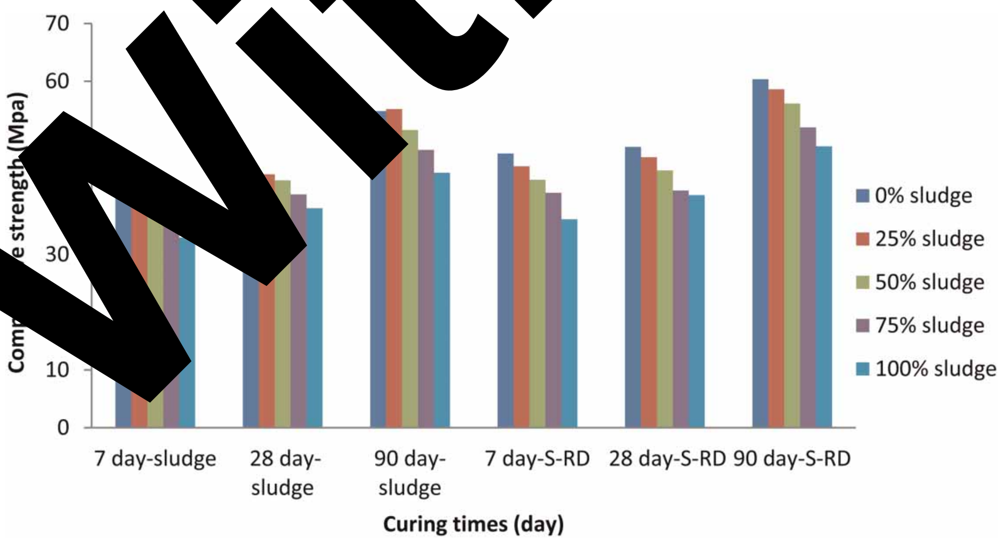

Figure 5 | Compressive strength according to the sludge and rock powder content with three different curing times.

Downloaded from http://iwaponline.com/jwrd/article-pdf/doi/10.2166/wrd.2014.031/221064/jwrd2014031.pdf
by guest

Uncorrected Proof

Withdrawn

concretes with sludge varied from about 33 to 55 MPa, while samples with sludge and rock dust fluctuate between 36 and 58.5 MPa. This means that strengths of specimens were improved by using rock dust, which enhanced the decreasing effects of sewage sludge on compressive strength of concretes. In general, all samples containing sludge with or without rock dust diminished their values with quantity progressively. Such behavior can be related to the presence of non-degradable organic matter in the sludge (Barrera-Díaza *et al.* 2011).

While the strength values of concretes without sludge showed a moderate increase with time, these amounts for specimens containing rock dust developed and showed higher quantities than the former ones. Moreover, the presence of rock dust in samples with 25 and 50% sludge as an alternative to freshwater provided more reinforcement compared to the conventional c[illegible]retes (without sludge and rock dust). This reveals the im[illegible]ng effect of rock dust on the compressive strengt[illegible] concrete.

CONCLUSION

The production of concret[illegible] the join[illegible]ition of sewage sludge and rock dus[illegible] offer a[illegible]cling alternative that is f[illegible]om t[illegible]ndpoint of compression stre[illegible]th and [illegible]ability. S[illegible] can be used in concrete [illegible] mixing w[illegible]p to 50% and can even increa[illegible]mpr[illegible] streng[illegible]ock dust is used instead [illegible]e aggr[illegible]. In othe[illegible] words, experimentally [illegible]anufact[illegible] sample[illegible]h recommended composite [illegible]been [illegible]ior in c[illegible]pressive strength compared [illegible]es. The workability of fresh concretes [illegible]nts a[illegible] trend in both usages of sludge, and th[illegible]mposite [illegible]ludge and rock dust. However, this [illegible]n is insignificant up to 50% replacement of [illegible] sludge, and the impact of rock dust is also cons[illegible]d negligible.

The production of concrete with a composite based on sewage sludge and rock dust can be effective from the viewpoint of environmental pollution control and natural resources conservation including freshwater and river aggregates.

ACKNOWLEDGEMENTS

We would like to convey sincere thanks to [illegible] Ali Babaei, due to the vast instructions for th[illegible]search [illegible] the respected personnel of Sang Salar [illegible]e would [illegible] like to express our highest appr[illegible]tion [illegible]e services rendered by Ravian Danesh Mohi[illegible]mpany [illegible]oviding insightful comments and pr[illegible]eading [illegible]he manu[illegible]ript.

REFERENCES

Abbaspou[illegible] & S[illegible]ejad, A. 2004 Design of an envi[illegible]menta[illegible]t model on the effect of vehicle [illegible]mis[illegible]n in[illegible]ater [illegible]on air pollution with economic [illegible]nsitivity[illegible]. *J. E[illegible]on. Sci. Tech.* **1** (1), 27–38.

A[illegible]ad, B., Ba[illegible]Hassan, S. 2006 Effect of sewage water on spinach y[illegible]*nt. J. Agric. Bio.* **3**, 423–425.

A[illegible]P. C. 2000 Cements of yesterday and today: concrete of [illegible]row. *Cem. Concr. Res.* **30** (9), 1349–1359.

ASTM [illegible]6 1996 *Standard Test Method for Sieve Analysis of Fine* [illegible]*nd Coarse Aggregates*. American Society for Testing and Materials, USA & Canada.

[illegible] C143-90a 1998 *Standard Test Method for Slump of Hydraulic Cement Concrete*. American Society for Testing and Materials, USA & Canada.

ASTM C109-99 1999 *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars*. American Society for Testing and Materials, USA & Canada.

Barrera-Díaza, C., Martínez-Barrerab, G., Gencelc, O., Bernal-Martíneza, L. A. & Brostowd, W. 2011 Processed wastewater sludge for improvement of mechanical properties of concretes. *J. Hazard. Mater.* **192**, 108–115.

Chatveera, B. & Lertwattanaruk, P. 2009 Use of ready-mixed concrete plant sludge water in concrete containing an additive or admixture. *Environ. Manage.* **90** (5), 1901–1908.

Donatello, S., Freeman-Pask, A., Tyrer, M. & Cheeseman, C. R. 2010 Effect of milling and acid washing on the pozzolanic activity of incinerator sewage sludge ash. *Cement Concr. Compos.* **32**, 54–61.

Eires, R. & Jalali, S. 2005 Not conventional materials for a sustainable construction: a bioconstruction system reinforced with cellulose fibers. In *Portuguese Materials Society Meeting-12 International Materials Symposium*, CICECO, Portugal.

Fotovat, A., Alavi Moghadam, M. R., Maknoon, R. & Sebt, M. H. 2007 Laboratory study on application of municipal sludge ash in construction materials. In *Proceedings of IWA special conference on Facing Sludge Diversities, Challenges, Risks and Opportunities*, Belek, Antalya, Turkey, pp. 28–31.

Fytili, D. & Zabaniotou, A. 2006 Utilization of sewage sludge in EU application of old and new methods – a review. *Renew. Sustain. Energy* **12**, 116–140.

Downloaded from http://iwaponline.com/jwrd/article-pdf/doi/10.2166/wrd.2014.031/221064/jwrd2014031.pdf
by guest

Uncorrected Proof

Withdrawn

Hoffman, A. 2000 *Competitive Environmental Strategy: A Guide to the Changing Business Landscape*. Island Press, Washington, DC.

Ilangovan, R. & Nagamani, K. 2006 Studies on strength and behavior of concrete by using quarry dust as fine aggregate. *CE CR J New Delhi* **3** (5), 40–42.

Ilangovana, R., Mahendrana, N. & Nagamanib, K. 2008 Strength and durability properties of concrete containing quarry rock dust as fine aggregate. *ARPN J. Eng. Appl. Sci.* **3** (5), 1819–6608.

Joo, T. 1989 Reclamation of wastewater and sludge for concrete making. *HWA Resour. Conserv. Recycl.* **2**, 211–227.

Joo, T. & Kuan, Y.-S. 1994 Municipal wastewater sludge as cementitious and blended cement materials. *Cem. Concr. Comp.* **16**, 39–48.

Kanitha, M., Ramya, P., Revathi, V. & Bhuvanya, S. 2014 Potential utilization of untreated/treated textile effluent in concrete. *Int. J. Res Eng. Technol.* **3**, 2321–7308.

Khalilzadeh, E. & Marandi, R. 2012 Evaluation of heavy metals leakage from concretes containing municipal wastewater sludge. *Environ. Pollut.* **1** (2), 176–182.

Lee, O. S., Salim, M. R., Ismail, M. & Ali, M. I. 2001 Reusing trea[illegible] effluent in concrete technology. *J. Teknologi* **34** (F), 1–10.

Leung, H. Y., Balendran, R. V., Maqsood, T., Nadeem, A., Rana, T. M. & Tang, W. C. 2003 Fibre reinforced polymer materi[illegible] for prestressed concrete structures. *Struct. Surv.* **21** (2), [illegible] 101.

Lina, Y., Zhoua, S., Li, F. & Lina, Y. 2012 Utilization of muni[illegible] sewage sludge as additives for the production [illegible] eco-ceme[illegible] *J. Hazard. Mater.* **213–214**, 457–[illegible]

Malliou, O., Katsioti, M., Georgiadis, [illegible] Ka[illegible], A. 2[illegible] Properties of stabilized/solidified a[illegible]s of ceme[illegible] sewage sludge. *Cem. Con[illegible] Comp.* **29**, [illegible]

Mohammad, M. J. & Athamn[illegible] 2004 C[illegible]s in soil fertility and plant uptake [illegible]nts and h[illegible]etals in response to se[illegible] sludg[illegible]on to calca[illegible] soils. *J. Agron.* **3** (3), 22[illegible]–236.

Mun, K. J. 20[illegible] Develop[illegible]nd tests [illegible]t aggregate using sew[illegible]ludge fo[illegible]tructural [illegible]ete. *Construct. Build. Mate[illegible]* 1583–1[illegible]

Na[illegible]hana, H[illegible] B. 2011 [illegible]rushed rock powder as [illegible]nt of [illegible]ggregate in [illegible]ortar and concrete. *Indian* [illegible] 4[illegible]17–922.

Nand[illegible]dhikes[illegible]iya, K. & Moharana, N. C. 2010 St[illegible]rusher d[illegible]e aggregate in concrete for paving bloc[illegible] *t. J. Civil St[illegible]ct. Eng.* **1** (3), 613–620.

[illegible] A. [illegible]005 *Properties of Concrete*. 6th and final edn., [illegible]ley Longman, UK.

Noruzma[illegible]hammad, B. & Abdul-Majid, I. M. Z. 2012 Characte[illegible]stics of treated effluents and their potential applications for producing concrete, *t. J. Environ. Manage.* **110**, 27–32.

Oakes, E. Z. H. S. R. 2002 Investigation of alleged health incidents associated with land application of sewage sludge. *New Solut.* **12**, 387–408.

Onaka, T. 2000 Sewage can make Portland cement: a n[illegible] technology for ultimate reuse of sewage sludge. *W[illegible]er Sci. Technol.* **41**, 93–98.

Pescod, M. B. 1992 Wastewater treatment and [illegible]se in [illegible]ture. FAO irrigation and Drainage Publicati[illegible] Italy.

Sahu, A. K., Sunil, K. & Sachan, A. K. 2003 Cru[illegible] stone w[illegible] aggregate for concrete. *Indian C[illegible]rete J.* [illegible]45–848.

Sales, A. & Rodrigues de Souza, F. [illegible]ret[illegible]d mortars recycled with water treatment sl[illegible]a[illegible]tion and demolition rubble. *Co[illegible] Buil[illegible]ater.* [illegible]2–2370.

Sales, A., Rodrigues de Souza, [illegible]es[illegible] Santos, W., Mendes Zimer, A. & do C[illegible]to Rosa A[illegible]10 Lightweight composite co[illegible]duced with w[illegible] treatment sludge and sawdu[illegible]erm[illegible]erties and potential application. *Construct[illegible]ld. M[illegible]er.* [illegible]46–2453.

Sales, A. [illegible]odrigues d[illegible]ouza, [illegible]o Couto Rosa Almeida, F. 20[illegible]echanica[illegible]pertie[illegible]f concrete produced with a [illegible]osite of wa[illegible]nt sludge and sawdust. *Construct.* [illegible] *Mater.* **25**, 2[illegible]–2798.

Shahu[illegible]ed, M. & Sekar, A. S. S. 2009 Properties of green conc[illegible]ntaining quarry rock dust and marble sludge powder [illegible] aggregate. *ARPN J. Eng. Appl. Sci.* **4** (4), 83–[illegible]

Sou[illegible] & Shrihari, D. S. 2007 Disposal of incinerator ash by [illegible]g to concrete. In *Proceedings of the International Conference on Sustainable Solid Waste Management*, 5–7 September 2007, Chennai, India, pp. 398–405.

Tamrabet, L., Bouzerzour, H., Kribaa, M. & Makhlouf, M. 2009 The effect of sewage sludge application on durum wheat (Triticum durum). *Int. J. Agric. Biol.* **11**, 741–745.

Taruya, T., Okuno, N. & Kanaya, K. 2002 Reuse of sewage sludge as raw material of Portland cement in Japan. *Water Sci. Technol.* **46**, 255–258.

Torabian, A. & Moumeni, L. 2003 Municipal sewage sludge management plan (case study: Shahrak Qods treatment plan). *J. Environ. Stud.* **28** (30), 65–78.

Valls, S., Yagüe, A., Vázquez, E. & Mariscal, C. 2004 Physical and mechanical properties of concrete with added dry sludge from a sewage treatment plant. *Cem. Concr. Res.* **34**, 2203–2208.

Wanga, X., Jin, Y., Wang, Z., Nie, Y., Huang, Q. & Wanga, Q. 2009 Development of lightweight aggregate from dry sewage sludge and coal ash. *Waste Manage.* **29**, 1330–1335.

Yagüe, A., Valls, S., Vázquez, E. & Albareda, F. 2005 Durability of concrete with addition of dry sludge from waste water treatment plants. *Cem. Concr. Res.* **35**, 1064–1073.

Zelic, J. 2005 Properties of concrete pavements prepared with ferrochromium slag as concrete aggregate. *Cem. Concr. Res.* **35**, 2340–2349.

First received 23 April 2014; accepted in revised form 2 August 2014. Available online 8 September 2014

Downloaded from http://iwaponline.com/jwrd/article-pdf/doi/10.2166/wrd.2014.031/221064/jwrd2014031.pdf
by guest