Effects of Washwater Sludge Obtained From Ready-Mixed Concrete Plants on Hydration and Mechanical Properties of Mortar

A. G. Gedik[1], Ü. A. Doğan[2]

[1]Department of Civil Engineering, ITU, Istanbul, Turkey, gedika@itu.edu.tr

[2]Department of Civil Engineering, ITU, Istanbul, Turkey, doganunal@itu.edu.tr

Abstract

This study was conducted to assess the usage of a waste material collected by a filtration mechanism applied in washing process of concrete transmixers in mortars with the aim of evaluating a potential sustainable concrete production.

Increasing consumption of building materials has compelled the construction industry to think about ways to sustain resources such as concrete and its derivatives. In line with this purpose, the objective of this experimental study is set to eliminate the washwater sludge material in ready-mixed concrete (RMC) plants by using it as an additive or as a replacement material in mortar production. Washwater sludge obtained from a ready-mixed concrete plant was cut into pieces and dried at 110±5°C for 24 hours. Then, it was ground into the size of cement (<90 µm), and incorporated into mortar preparation in two sets. In the first set, the sludge was replaced with sand by weight. In the second one, the sludge was used as an addition in mortars. The properties of mortars such as compressive strength and hydration characteristics under constant temperatures of 10°C and 30°C in an isothermal calorimeter chamber were determined. The results demonstrated that as the sludge content increased, the strength gain was more rapid and better mechanical performances were observed. In addition to increasing the total heat of hydration in 3 days at 30°C, the washwater sludge contributed to the total heat of hydration even at 10°C that promotes the idea of using it as a hydration stimulating material in winter conditions. However, necessary precautions should be considered for hot weather conditions. The results illustrated that the reuse of washwater sludge in concrete is regardable with its positive influences on concrete properties and sustainability.

Keywords: *washwater sludge, sustainability, isothermal calorimeter, hydration*

1 Introduction

The remarkable increase in concrete production over the years has been resulted in an acceleration in the consumption of resources. However, the environmental and economic effects of concrete are not only related to resource consumption. Other effects can be summarized as the wastes generated as a result of concrete production and transportation, and the costs required for their disposal.

Concrete wastes are formed continuosly during the production of ready-mixed concrete. The followings are the main reasons of waste generation in ready-mixed concrete plants: the concrete adhering to the inner surface of the transmixers, the remaining concrete after pouring at the construction site, the concrete poured out of the transmixers due to operational errors, and the concrete taken as sample for the quality control tests (Kazaz et al., 2016).

The remaining fresh concrete is disposed after a series of treatment process. It is stated that washwater-fluid waste formed in RMC plants- poses a threat to environment due to its high alkanity (Özkul and Doğan, 2016). The idea of recycling concrete in ready-mixed concrete plants is important as it enables the reuse of aggregates and washwater in concrete production as well as preventing adverse effects on the environment such as land and water pollution. A data analysis conducted with one of the leading ready-mixed concrete manufacturers in Turkey showed that the amount of aggregates recovered in 26 facilities containing a recycling system in the last two quarters of 2019 was approximately 7.600 tons. According to the calculations made in the light of the information obtained, roughly 1.7 tons of aggregate were obtained from 1 m^3 of waste concrete in those facilities.

A widely used method to treat the fresh concrete in ready-mixed concrete plants is recruiting a system which can collect washwater, sludge and aggregates separately. In this method, transmixers are washed with tap water first in order to make the inner surface be free of fresh concrete prior to concrete gets hardened. Then, the waste product is transferred into a drum with spiral elements, which serves as a seperation unit. The aggregates and the mixture of washwater and fine particles exit the drum as two different phases. The washwater with high amount of suspended fine particles is collected in the settlement tanks and pumped into the filter press. The last products of the process are substantially treated washwater that can be used as mixing water in new concrete batches, and the washwater sludge. It was predicted that approximately 30 kg of sludge is obtained from 1 m^3 of residual concrete (Audo et al., 2018). The heavy metal content and high alkanity of the washwater sludge was reported before (Sealey et al., 2001). In addition, its cost of transportation to landfill areas is another problem to consider. Reusing it in concrete production may be beneficial in economic and environmental aspects.

Washwater sludge is a composition of a vast amount of hydrated cement, fine materials, water, and unhydrated cement, generally in negligible amounts. It was found that washwater sludge has a chemical composition between those of Portland cement and fly ash (Chatveera and Lertwattanaruk, 2009). However, calcium oxide (CaO) and silicon dioxide (SiO_2) components are not expected to be reactive as cement particles have already been hydrated (Anastasiou et al., 2018). The increased amount of SiO_2 in the sludge comparing to Portland cement might be due to the existence of sand in the produced concrete. It is also possible that the amount of CaO in the washwater sludge is less than the amount in Portland cement due to the washing process applied on residual fresh concrete. Due to the high water absorption capacity of washwater sludge, more water was required to be added to the mixtures including washwater sludge to obtain desired consistency (Kou et al., 2012). Another finding is that the angular grain structure of dry sludge prevents the excess water from moving upwards to the surface during placement, and brings about additional voids (Rughooputh et al., 2017).The replacement of dry sludge with cement at less than 2% by weight caused a slight improvement in compressive strength of mortars, showing a similar behavior with the limestone filler (Zervaki et al., 2013). The amount of hydration heat emission of the paste including only washwater sludge as binding material was found significant (Tang et al., 2019). It was also indicated that the washwater sludge in the matrix functions as nucleus sites, stimulating cement particles to hydrate more rapid at early ages (He et al., 2020).

This paper aims to contribute toward further understanding of washwater sludge manner in a way of using it as an addition or a replacement material in mortar. Effects on the compressive strength and hydration kinetics (hydration rate and total heat of hydration) were observed and discussed. The washwater sludge was collected from a ready-mixed concrete plant in Turkey.

2 Experimental

In this study, the washwater sludge was replaced with natural sand at 10% by weight, and it was incorporated as an addition at 20% by weight that of cement. The water-to-cement (w/c) ratios of 0.50 and 0.60 were selected for the mixtures. The compressive strengths at 3, 7, 28, and 90 days were carried out. The cumulative heat of hydration and heat flow rate curves were monitored for each sample over the time period of 72 hours using an isothermal calorimeter. The compressive strength test at 3 days is conducted in order to see the close link between the hydration mechanism and strength development.

2.1 Materials

CEM I 42.5 R Portland cement with specific gravity of 3.04 gr/cm^3 was used as binder material in all the mixtures. Natural sand with fineness modulus of 1.57 and specific gravity of 2.60 gr/cm^3 was incorporated. The washwater sludge obtained from RMC plant has a specific gravity of 2.78 gr/cm^3 in dry state, and the average particle size was found to be 12 µm. Hydrometer analysis confirmed that almost 95% of the sludge particles were able to pass through the No. 200 sieve (75 µm).

2.2 Preperation of Mortar Specimens

The washwater sludge samples were left to dry at 110±5°C for 24 hours, then passed through a #140 sieve (90 µm). Mix proportions with two w/c ratios (0.50 – 0.60) are presented in Table 1, in which R denotes the reference mortar including cement, natural sand and water, C-20 represents mortar in which the sludge was added at 20% by the weight of cement, and S-10 represents mortar in which the sludge replaced with natural sand at 10% by weight. The use of admixtures was avoided in order for the washwater sludge to be the only dominant affecting factor. Components were mixed and cast into 40x40x160 mm moulds as described in TS EN 196-1. Samples for heat of hydration were mixed externally and placed into plastic boxes that fit to the isothermal calorimeter chambers. External mixing caused loss of data in the first seconds of the hydration mechanism, as expected.

Table 1. Mix proportions of mortars.

Mix	**Proportion (g)**		
	Cement	**Sludge**	**Sand**
R	450	-	1350
C-20	450	90	1350
S-10	450	135	1215

2.3 Test Methods

The compressive strength of mortars at the ages of 3,7,28 and 90 days was performed in accordance with TS EN 196-1. The heat of hydration was tested using Calmetrix I-Cal 2000 HPC isothermal calorimeter with two channels.

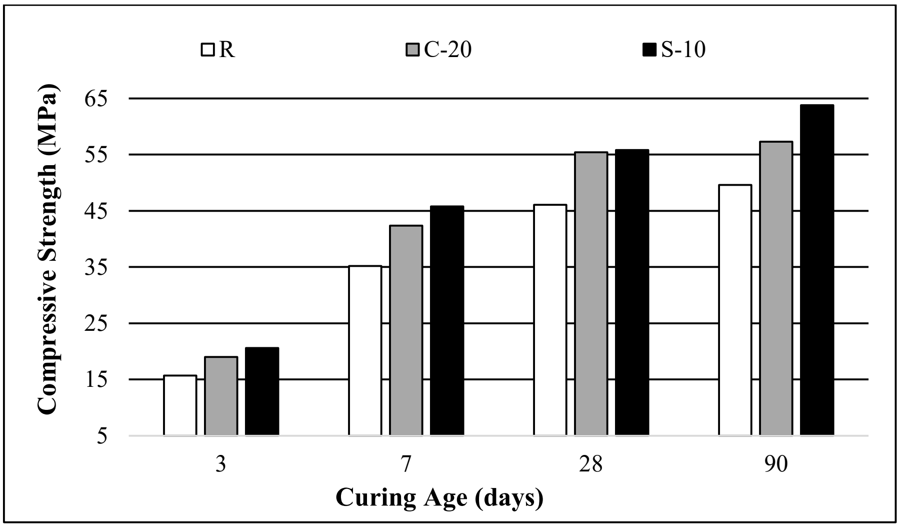
3 Results and Discussion

3.1 Compressive Strength

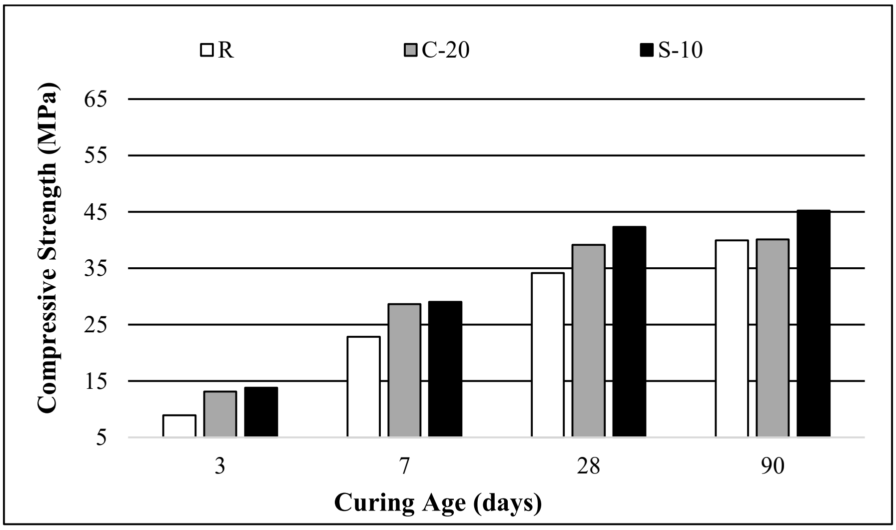
Figure 2 demonstrates the experiment results of the compressive strengths of all the mixtures at the ages of 3, 7, 28 and 90 days. The compressive strength values increased with time for both of the w/c ratios,and decreased with the increasing w/c ratio, as expected. The highest compressive strength values are those of mortars in which the washwater sludge was replaced with sand. This result was explained in two ways. First, the washwater sludge may have diminished the porosity of the matrix by functioning as a filler material. Secondly, the washwater sludge may have contained unhydrated cement particles that enables additional hydration reaction and creates a denser structure. Due to the specific gravity difference between cement and washwater sludge, the true cement content in unit volume of mortar was decreased by almost 4% with the addition of washwater sludge by weight. Nevertheless, C-20 samples had higher strength values than R samples at all ages.

Table 2 illustrates the relative compressive strengths. It is clearly observed that the early age compressive strength is higher when washwater sludge is employed. This might be due to the high pH value of the washwater sludge, leading to a faster formation of portlandite ($Ca(OH)_2$), and consequently reduction of Ca^{+2} ions in the solution

(Schöler et al., 2017) (Vollpracht et al., 2016). This reduction in the Ca^{+2} ions makes the dissolution of anhydrous components easier. The gap between the compressive strength values of reference and washwater sludge incorporated specimens decreased by time (Table 2).



(a)



(b)

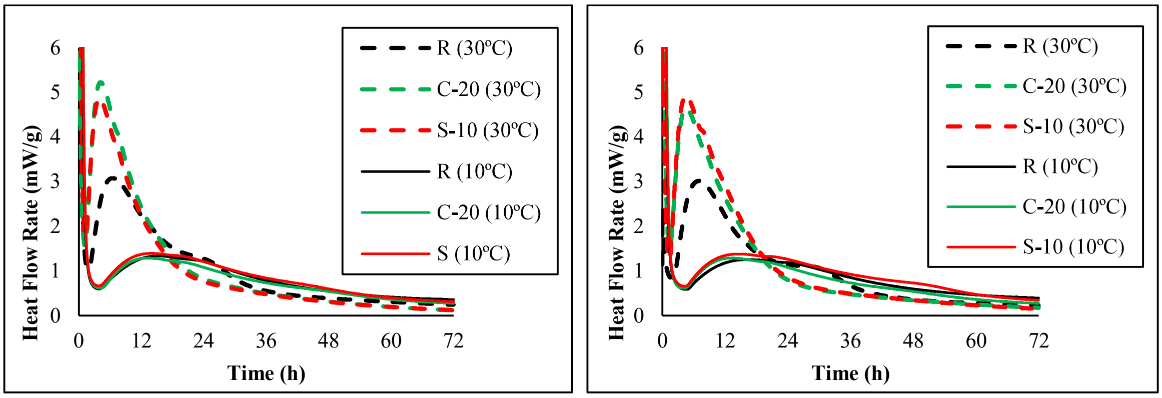
Fig. 2. Compressive strength of mortars: (a) w/c= 0.50; (b) w/c= 0.60

Table 2. Relative compressive strength of mortar (%).

Mix	W/C	3 days	7 days	28 days	90 days
R	0.50	100	100	100	100
C-20	0.50	121	120	120	116
S-10	0.50	131	130	121	129
R	0.60	100	100	100	100
C-20	0.60	147	125	115	101
S-10	0.60	155	127	124	113

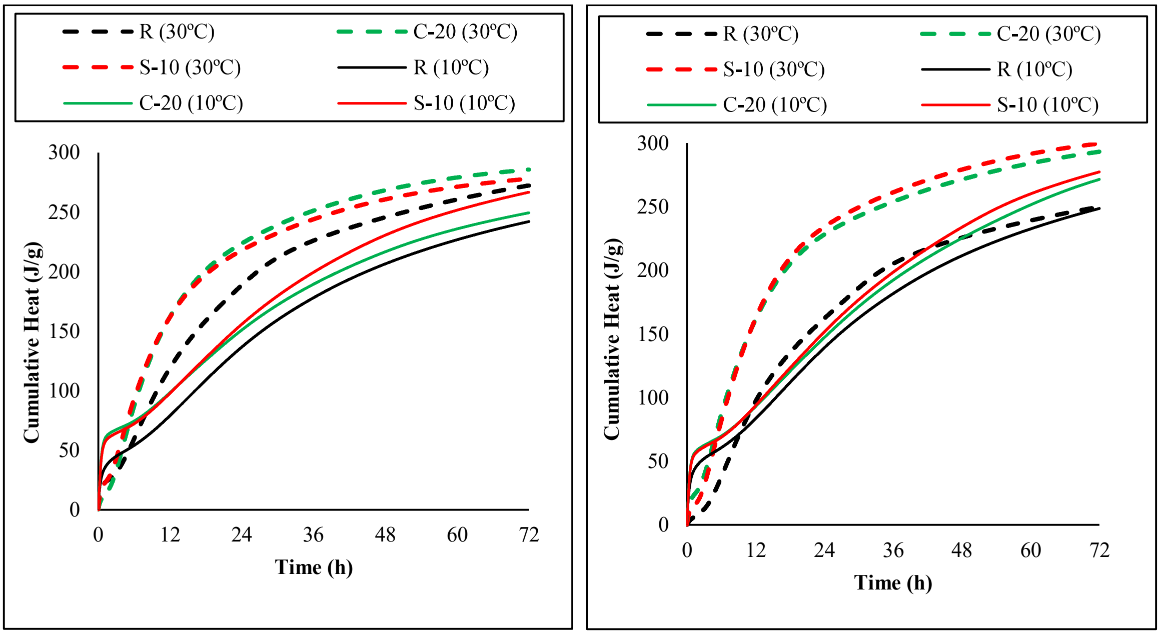
3.2 Hydration Characteristics

Fig. 3 shows the heat flow rate curves of mortars under the constant temperatures of 10ºC and 30ºC. Fig. 4 shows the total heat released during 72 h under the same constant temperatures. The characteristic hydration heat values of the samples are presented in Table 3.



(a) (b)

Fig. 3. Heat flow rate curves of mortars under 10ºC and 30ºC: (a) w/c= 0.50; (b) w/c= 0.60



(a) (b)

Fig. 4. Cumulative heat curves of mortars under 10ºC and 30ºC: (a) w/c= 0.50; (b) w/c= 0.60

Immediately after binding material contacted water, a very steep exothermic peak of aluminate phases and formation of ettringite were seen due to the reaction between calcium aluminate (C_3A) and sulfate in pre-induction period (Han et al., 2014) (Fig. 3a and 3b). This first peak was not apparently seen because of the external mixing method as stated above. Hydration process slowed down within a few minutes shortly after the ettringite formation. This typically occurs during the induction period of hydration mechanism (Beaudoin & Odler, 2004). The ending time of the induction period became shorter by replacing the washwater sludge with natural sand (Table 3). This trend remained for C-20 mortars in which washwater sludge is added by weight of cement at only 30ºC (Table 3). It was also observed that the dormant period of C-20 and S-10 mixtures lasted earlier than that of R.

During the first 12 h, the washwater sludge led to more heat release in all the mixtures even at the temperature of 10ºC. This period covers both initial setting and final setting times which are roughly located in the upward line (acceleration period) between the dormant period and main hydration peak. It was found that the washwater sludge shortened the initial and final setting times of all the samples. The usage of washwater sludge shifted the main hydration peak (second peak) to left and accelerated the hydration of cement, which can be mainly attributed to the reaction of tricalcium silicate (C_3S) (Fig. 3a and 3b).

As the temperature rised, hydration became more rapid, and a narrower second peak was formed for all the mixtures (Fig. 3a and 3b). Times of the second heat emission peaks were prolonged with the increase in w/c ratio, due to the decrease of alkali concentration in the solution. Moreover,the rate of the second heat emission peak values were generally higher at lower w/c ratio (Table 3).

The deceleration period started after 12 h for the samples at 10ºC and earlier than 12 h at 30ºC. A third shoulder peak known as sulfate depletion peak after the main hydration was seen for the washwater sludge incorporated mixtures at 30 ºC (Sandberg and Roberts, 2005) (Fig. 3a and 3b). This was related to renewed C_3A reaction (Andrade Neto et al., 2021). It is a known fact that hydration of aluminate phase is affected by the presence of sulfates. When the sulfate concentrations are high, the reaction of C_3A is suppressed (Schöler et al., 2017).

At the end of 72 h, hydration process was still going on at a very low rate and the heat flow rate of R was higher than the other mixtures. This result was attributed to more consumption of anhydrous components in the mortars including washwater sludge, leaving less amount of particles and water to hydrate, and lack of space in the matrix. The gap between the reference mortar and washwater sludge incorporated mortars was closed with time in terms of cumulative heat (Fig. 4a and 4b).

The results demonstrate that hydration is affected by the presence of washwater sludge in the mixtures. Its stimulating influence on hydration mechanism can be attributed to the filler effect asserting that a filler material is considered as inert and acts as a nucleation core for the hydration of alite and belite components in cement (Ye et al., 2007). The washwater sludge strengthened the adherence between cement particles, and accelerated the hydration by nucleus effect (He et al., 2020).

It was understood that the washwater sludge increased the rate of dissolution of cement in water and formation of hydration products, especially in the first hours of the reaction. The 3 days compressive strength values were consistent with hydration heat values. These results support the correlation between hydration mechanism and strength development.

Table 3. Hydration heat values of the samples

T (°C)	**Sample**	**W/C**	**Total heat emission (J/g)**				**Ending time of the induction period (h)**	**Rate of the second heat emission peak (mW/g)**	**Time of the second heat emission peak (h)**
			12 h	**24 h**	**48 h**	**72 h**			
10	R	0.50	79	137	207	242	4,1	1,40	15,1
10	C-20	0.50	99	151	217	249	4,2	1,29	13,1
10	S-10	0.50	98	156	231	267	3,9	1,40	13,8
10	R	0.60	84	139	212	249	4,5	1,34	16,0
10	C-20	0.60	93	147	225	272	4,5	1,30	14,6
10	S-10	0.60	94	152	234	277	4,3	1,38	14,3
30	R	0.50	119	189	246	272	1,8	3,08	6,6
30	C-20	0.50	162	224	268	286	1,2	5,23	4,2
30	S-10	0.50	162	218	261	278	1,3	4,85	4,0
30	R	0.60	97	162	226	250	1,8	3,02	7,0
30	C-20	0.60	162	228	272	293	1,4	4,64	4,7
30	S-10	0.60	163	234	279	300	1,3	4,92	4,6

4 Conclusion

The study presented herein is set to draw attention to a potential sustainable usage of the washwater sludge from ready-mixed concrete plants by expressing its effects on compressive strength and hydration.

The hydration heat and compressive strength results showed that rapid hydration occurs and significant early strength development is obtained by usage of the washwater sludge. Replacing it with natural sand influenced hydration kinetics and mechanical properties more specifically. Cumulative heat values and hydration heat curves obtained are promising for using it in concrete productions in winter conditions, while the risk of thermal cracks occuring must always be considered at elevated temperatures. According to compressive strength test results it is clear that the washwater sludge contributes to the strength even at later ages.

References

Anastasiou, E., Papachristoforou, M., Anesiadis, D., Zafeiridis, K., & Tsardaka, E. C. (2018). Investigation of the use of recycled concrete aggregates originating from a single ready-mix concrete plant. *Applied Sciences (Switzerland)*, *8*(11). https://doi.org/10.3390/app8112149.

Andrade Neto, J. da S., De la Torre, A. G., & Kirchheim, A. P. (2021). Effects of sulfates on the hydration of Portland cement – A review. Construction and Building Materials, 279. https://doi.org/10.1016/j.conbuild mat.2021.122428.

Audo, M., Mahieux, P. Y., Turcry, P., Chateau, L., & Churlaud, C. (2018). Characterization of ready-mixed concrete plants sludge and incorporation into mortars: Origin of pollutants, environmental characterization and impacts on mortars characteristics. Journal of Cleaner Production, 183, 153–161. https://doi.org/10.1016/j.jclepro.2 018 .02.155.

Beaudoin, J., & Odler, I. (2004). Hydration, Setting and Hardening of Portland Cement. In Lea's Chemistry of Cement and Concrete (Fourth Edi). Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100773-0.00005-8.

Chatveera, B., & Lertwattanaruk, P. (2009). Use of ready-mixed concrete plant sludge water in concrete containing an additive or admixture. Journal of Environmental Management, 90(5), 1901–1908. https://doi.org/10.10 16/j.jenvman.2009.01.008.

Han, F., Liu, R., Wang, D., & Yan, P. (2014). Characteristics of the hydration heat evolution of composite binder at different hydrating temperature. Thermochimica Acta, 586, 52–57. https://doi.org/10.1016/j.tca.2014.04.010.

He, X., Zheng, Z., Ma, M., Su, Y., Yang, J., Tan, H., Wang, Y., & Strnadel, B. (2020). New treatment technology: The use of wet-milling concrete slurry waste to substitute cement. Journal of Cleaner Production, 242, 118347. https://doi.org/10.1016/j.jclepro.2019.118347.

Kazaz, A., Ulubeyli, S., Er1, B., Arslan, A., & Atici, M. (2016). European Journal of Engineering and Natural Sciences Identification of Waste Sources in Ready-Mixed Concrete Plants. European Journal of Engineering and Natural Sciences CODEN, 1(1), 9–14.

Kou, S. C., Zhan, B. J., & Poon, C. S. (2012). Feasibility study of using recycled fresh concrete waste as coarse aggregates in concrete. Construction and Building Materials, 28(1), 549–556. https://doi.org/10.1016/j.conbuild mat.2011.08.027.

Özkul, M. H., & Doğan, Ü. A. (2016). Transmikser yıkama suyunun hazır beton üretiminde geri dönüşümü. Hazır Beton Dergisi (Eylül-Ekim 2016), 82–86.

Rughooputh, R., Rana, J. O., & Joorawon, K. (2017). Possibility of using fresh concrete waste in concrete for non structural civil engineering works as a waste management strategy. KSCE Journal of Civil Engineering, 21(1), 94–99. https://doi.org/10.1007/s12205-016-0052-1.

Sandberg, P. J., & Roberts, L. R. (2005). Cement-admixture interactions related to aluminate control. Journal of ASTM International, 2(6), 219–232. https://doi.org/10.1520/jai12296.

Schöler, A., Lothenbach, B., Winnefeld, F., Haha, M. Ben, Zajac, M., & Ludwig, H. M. (2017). Early hydration of SCM-blended Portland cements: A pore solution and isothermal calorimetry study. Cement and Concrete Research, 93, 71–82. https://doi.org/10.1016/j.cemconres.2016.11.013.

Sealey, B. J., Phillips, P. S., & Hill, G. J. (2001). Waste management issues for the UK ready-mixed concrete industry. Resources, Conservation and Recycling, 32(3–4), 321–331. https://doi.org/10.1016/S0921-3449(01)00069-6

Tang, P., Xuan, D., Poon, C. S., & Tsang, D. C. W. (2019). Valorization of concrete slurry waste (CSW) and fine incineration bottom ash (IBA) into cold bonded lightweight aggregates (CBLAs): Feasibility and influence of binder types. Journal of Hazardous Materials, 368(January), 689–697. https://doi.org/10.1016/j.jhazmat.2019.01.112.

Turkish Standards Institution. (2016). *Methods of testing cement - Part 1: Determination of strength* (TS EN 196-1.2016).

Vollpracht, A., Lothenbach, B., Snellings, R., & Haufe, J. (2016). The pore solution of blended cements: a review. Materials and Structures/Materiaux et Constructions, 49(8), 3341–3367. https://doi.org/10.1617/ s11527-015-0724-1.

Ye, G., Liu, X., De Schutter, G., Poppe, A. M., & Taerwe, L. (2007). Influence of limestone powder used as filler in SCC on hydration and microstructure of cement pastes. Cement and Concrete Composites, 29(2), 94–102. https://doi.org/10.1016/j.cemconcomp.2006.09.003.

Zervaki, M., Leptokaridis, C., & Tsimas, S. (2013). Reuse of by-products from ready-mixed concrete plants for the production of cement mortars. Journal of Sustainable Development of Energy, Water and Environment Systems, 1(2), 152–162. https://doi.org/10.13044/j.sdewes.2013.01.0011.