An Experimental Study on Construction and Demolition Waste Usage as Secondary Raw Material for Cement Production

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***Abstract*— In the present study, an investigation was conducted to evaluation of tile, brick, fire brick, plaster and concrete wastes derived from construction and demolition (C&D) wastes in Portland cement raw meal production as secondary raw material. Clinker test results showed that using of these wastes in cement was suitable. Then, cement production was performed with using 1, 2.1 and 3.9 wt. % mix C&D waste addition ratios in the cement factory. Desired phases like belite and alite, which are essential for the cement products, were observed at the micrographs. Also, obtained cement products supplied required and standard properties; however, strength and hydration heat values were lower. Finally, optimum C&D waste addition ratio was determined and results were found as practicable. It was shown that mix C&D waste materials can be utilized as secondary raw material in cement production.**

***Index Terms*— Cement, clinker, construction and demolition waste, recycling and reusing.**

I. Introduction

Urban transformation process accelerated in recent years because of rapid population growth and majority of old buildings in Istanbul, Turkey. As a consequence of these renewal process, huge amount of construction and demolition (C&D) wastes occur and constitute one of the biggest environmental problems.

In recent years, energy consumption and CO_2 emission issue gained importance especially in construction and building sector. Using of recycled construction wastes is one of the potential environmental solutions for production of building materials [1]. C&D wastes are recycled as a ratio of nearly 46 % in the European Union's 27 member countries. The highest C&D waste recycling rates are 98, 94, 92 and 86 % in Holland, Denmark, Esthonia and Germany, respectively [2].

C&D waste materials consist of mainly stony proportions like brick, tile, ceramic materials, concrete, stone, sand, gravel etc. To utilize these waste materials in various sectors were investigated and lots of studies were conducted by many researchers [3]-[11].

Puertas et al. (2008) investigated the effects of fired red and/or white ceramic wall tile waste on reactivity and burnability properties of cement mixtures. After using of these wastes as alternative raw material in cement production, it was seen that obtained mixtures satisfied the technical properties with having higher burnability and reactivity values than common cement mixtures. While mineralogical contents of obtained cement samples was similar to conventional cements, some oxides like ZnO, ZrO_2 and B_2O were higher because of tile glazing on waste materials. On the other hand, because of the mixture produced with using waste materials has no need to sand, which contains high amount of chromium, the obtained clinkers had lower chromium value than common clinkers. Finally, it was seen that the red ceramic wall tile wastes caused more reactive mixtures because of having higher Fe_2O_3 content. Also, unseparated ceramic wastes (combination of red and white ceramic wall tile waste) supplied required values and it was shown that there is no need to separate these different types of wastes due to the fact that obtaining technically proper materials [5].

Galbenis et al. (2004) executed a study to evaluate recycled concrete aggregates and rubbles obtained from C&D waste as alternative raw material in clinker production. Chemical composition of waste materials were measured as follows: 52.75 – 54.75 % CaO, 1.23 – 2.84 % SiO_2, 0.57 – 0.96 % MgO, 0.27 – 0.43 % Fe_2O_3 and lower than 68 % Al_2O_3. The main mineralogical phases were observed as calcite and quartz, LOI value was measured as 41.94 – 42.94 %. These wastes were specified having similar chemical structure with natural clinker raw materials. Thus, substitution of recycled concrete aggregates and rubbles from the C&D wastes instead of the natural raw materials were suggested into clinker production [12].

In the study conducted by De Schepper et al. (2011), a research was executed about using of concrete wastes in clinker production as raw material. A concrete which was chemically suitable for clinker raw material was designed and produced with having these chemical properties: LSF: 0.94, SM: 2.66, AM: 3.62 and HM: 2.16. Produced concrete was milled, transformed into raw material and then fired at three different temperature 1350, 1400 and 1450°C. Optimum firing temperature was determined as 1450°C when microscopic and XRF analyses were examined. Finally, strength value of the mortar, which was produced with plaster addition, supplied a value closed to standard strength as 45.88 MPa [13].

Sumardi et al. (2005) studied about production of Portland cement with using demolishing wastes of house and buildings. To achieve required clinker modules, some

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recoverer and additional materials like limestone and brick waste were used and substitution ratio of raw materials were represented as follow: concrete waste: limestone: brick waste: 1: 3.489: 0.667. Clinker which contains minimum free calcite was produced with LSF: 0.86 and SM: 2.14 values at 1400°C for 30 min [14].

In the study conducted by Gastaldi et al. (2015), recovery of hydrated cement from C&D waste was investigated. Chemical composition and elemental ratios of hydrated cement waste (HCW) were found proper to use in cement and clinker production. It was observed that HCW contained amorphous calcium silicate, calcium aluminate hydrates, calcium hydroxide and minor amount of calcium/magnesium carbonate. Then, pure HCW was added into limestone and schist with different substitution ratios at clinker production. After HCW addition with a ratio of 30 %, it was seen that mineralogical properties of obtained clinker was compatible with reference clinker. When addition ratio of HCW increased to 55 %, calcium silicates amounts increased and also higher amounts of HCW using as cementing material supplied production of valuable non-Portland clinker. Both two substitution ratio (30% and 55%) caused lower CO_2 emmission during clinker/cement production. Moreover, it was shown that HCW can be used as alternative raw material depending on chemical properties of waste materials [15].

In the present study, different types of C&D wastes such as fire brick, brick, plaster, tile and concrete waste materials were separately obtained and used as alternative raw material in cement production. Optimum addition ratio was investigated with applying industrial scale experiments. Finally, it was shown that C&D waste materials can be preferred by cement factories with specified substitution ratios and cement/clinker production can be successfully carried out with obtaining required technical properties.

II. MATERIALS & METHODS

A. *Materials*

In this study, five different types of C&D waste materials were investigated to use as alternative raw material instead of limestone, shale, sand and grid in cement production process. Waste materials used in the study were named as in Table 1:

Table 1. Definition of waste materials used in this study.

Material name	Code	Grain size (mm)
Brick waste	BW	0-5
Fire brick waste	FBW	0-5
Tile waste	TW	0-5
Plaster waste	PW	0-5
Concrete waste	CW	0-5, 0-12, 5-12, 12-22, 12-38, 22-38

Waste materials were obtained from ISTAC Co. Waste Field. It should be noted that the exact source and age of the samples were unknown. Because of the cement production tests were applied on a facility “AKCANSA Co. Cement Factory”, characterization studies were based on and compared with the cement and clinker test results of this cement factory. Within this scope, physical, chemical and mineralogical analyses were applied on waste materials.
Primary raw materials used in cement production and waste materials were milled in the same mill with equal milling time to achieve homogeneous grain size distribution. According to sieve analysis, it was seen that grinding of C&D waste materials were more difficult.

B. *Wet Chemical Analysis*

Wet chemical analyses of crushed waste materials were done according to TS EN 196-2 standard [16] and results were shown in Table 2. It can be seen that SiO_2, Al_2O_3 and Fe_2O_3 contents of all kinds of waste materials are higher according to Portland cement. Also, plaster and concrete wastes have higher CaO content than other waste materials. Carbonate contents and loss on ignition (LOI) values of waste materials were seen as being quite lower than Portland cement. Because of the waste material compositions was not so close the Portland cement compositions, limited addition ratios were studied at the experiments.

Table 2. Chemical composition of raw materials

Material	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	Cl^- (%)	$CaCO_3$ + $MgCO_3$ (%)	LOI (%)
TW	66.90	12.93	8.16	2.46	2.06	0.47	1.13	2.17	0.0345	1.25	2.88
FBW	57.93	9.47	12.32	9.35	6.12	0.40	1.00	1.52	0.0312	5.75	1.65
BW	52.92	12.89	10.13	8.51	7.72	0.55	1.20	2.15	0.0355	9.00	2.99
PW	57.59	6.62	1.94	16.02	1.38	0.39	0.77	1.78	0.0371	27.75	13.01
CW	48.52	5.96	3.25	17.94	0.22	1.12	1.16	0.54	0.0125	31.00	21.26
Portland cement raw meal	13.12	3.09	2.64	43.61	0.96						35.5

C. *Moisture and $CaCO_3$ Determination*

Calcite ($CaCO_3$) is important because of being the main raw material in cement production and burning into CaO and CO_2 at nearly 1000°C. During cement production process, consisted CaO reacts with other compounds and creates the main phases of clinker in the furnace such as calcium silicates (alite Ca_3SiO_5, belite Ca_2SiO_4), calcium aluminates ($Ca_3Al_2O_6$) and calcium aluminoferrite ($Ca_2(Al,Fe)_2O_5$). For this reason, moisture and $CaCO_3$ contents of the waste materials were measured and results were illustrated in Table 3. Moisture and calcite content values of raw materials were determined from weight loss of materials after drying in oven at 105ºC and acid base titration, respectively. Waste materials moisture contents of were low and this can be an advantage in production process. Concrete waste materials calcite contents are higher than the other waste materials.

Table 3. Moisture and $CaCO_3$ contents of waste materials

Waste material	H_2O (%)	$CaCO_3$ (%)
TW (0-5 mm)	2.80	6.5
FBW (0-5 mm)	0.20	3.5
BW (0-5 mm)	0.20	8.0
PW (0-5 mm)	2.20	28.3
CW (22-38 mm)	9.20	24.5
CW (12-38 mm)	6.80	24.80
CW (12-22 mm)	3.80	31.5
CW (5-12 mm)	6.40	35.3
CW (0-12 mm)	6.80	25.5
CW (0-5 mm)	6.80	25.5

D. Heavy Metal Analysis

C&D wastes can contain heavy metals generating from dye, plastered, coating and insulation materials. Heavy metal containing of the waste materials which are going to evaluate as alternative raw materials in cement production is important. If these heavy metals are volatile at low temperature, they can mix with emission. High Cr content in the cement causes eczema occurrence on the skin. For this reason, Cr content for higher than 2 ppm is rejected in Europe.

To determine any problem occurring from using C&D waste material in cement production, heavy metal analysis was made by using Varian ICP-OES device. Requested heavy metal contents of clinker and measured heavy metal contents of C&D waste materials were compared and illustrated in Table 4. Cr content in concrete waste was measured to be high (185.34 ppm); however, whole heavy metals were evaluated according to the waste feeding ratios and the penetrated content into absorbed clinker. On the other hand, volatile heavy metal contents of C&D wastes were found to be low. After chemical analyses, it was seen that these waste material usage was theoretically suitable according to AKCANSA Co. Cement Factories raw material requirements. It should be noted that the result of suitableness can be different for other cement factories.

Table 4. Heavy metal concentrations in waste materials and limit values for clinker

Heavy Metal	Limit values for clinker (mg/kg)	TW (mg/kg)	FBW (mg/kg)	BW (mg/kg)	PW (mg/kg)	CW (mg/kg)
Arsenic (As)	<2-87	2.35	3.23	24.00	6.83	10.84
Boron (B)		67.41	55.23	136.75	34.10	36.21
Barium (Ba)		280.46	621.14	154.04	78.91	96.82
Beryllium (Be)		0.54	1.81	2.27	0.56	0.54
Cadmium (Cd)	0.01-1.5	1.81	2.13	3.96	0.56	1.00
Cobalt (Co)	<10-21	16.86	12.56	40.56	5.04	7.84
Chrome (Cr)	<10-319	189.43	199.33	277.91	151.22	185.34
Copper (Cu)	<5-136	23.55	20.08	52.52	7.24	13.65
Magnesium(Mg)		4998.3	2580.65	15612.2	3900.12	10943.8
Molybdenum (Mo)		<0.014	2.67	3.47	0.89	1.19
Manganese (Mn)		618.62	664.20	1008.57	292.92	466.97
Nickel (Ni)	<10-397	47.42	50.60	163.60	35.53	27.69
Lead (Pb)	<1-105	6.47	12.72	7.90	6.80	8.32
Antimony (Sb)	0.1-1.5	<0.012	<0.012	<0.012	<0.012	<0.012
Selenium (Se)	0.2<1.0	<0.012	4.50	<0.012	<0.012	<0.012
Strontium (Sr)		28.20	30.50	196.47	291.62	384.49
Titanium (Ti)	<0.01-1.2	2299.32	1538.21	4600.13	618.29	462.10
Vanadium (V)	10-135	35.89	19.04	137.09	30.66	30.43
Zinc (Zn)	29-531	52.42	36.33	97.10	24.55	33.09
Mercury (Hg)	<0.01-0.05	0.0082	0.0066	0.0058	0.0157	0.0281

III. EXPERIMENTAL STUDY

A. Burnability Test

To determine the effects of waste materials on burnability index, these waste materials were substituted instead of original raw materials and mixture ratios were represented in Table 5. While original cement mixture (M0) was based as reference for comparison, 5 different mixtures coded as M1, M2, M3, M4 and M5 were prepared with using 5 different C&D waste addition ratios. Because of having similar silica, aluminum and iron content, tile wastes were used instead of shale. Fire brick and brick wastes were used instead of grit raw material due to having high iron content. Plastered wastes were preferred instead of sand because of having high silica content. Concrete wastes haven't high amount of silica and calcium content, thus they were chosen as grit resource.

The applied burning process was common in all mixtures. The cement raw meals were first formed into small spheres, with a diameter of between 1 and 1.5 cm, and dried at 110°C for one day. They were placed in an electrical furnace at 1350°C, 1400°C, 1450°C and 1500ºC for 15 min. At the end of the process, samples were rapidly cooled in air.

Table 5. Mixture ratios for burnability test

	Mixture ratios for burnability test (%)					
	M0	**M1**	**M2**	**M3**	**M4**	**M5**
Lime stone	75.39	78.68	75.31	76.08	71.59	66.48
Shale	15.98		13.94	4.08	11.48	5.31
Grit	1.85	0.61			2.16	
Sand	6.79	3.27	1.64	4.12		2.41
TW		17.45				
FBW			9.10			
BW				15.72		
PW					14.77	
CW						25.81
Total	100.01	100.01	99.99	100	100	100.01

BI values are categorized into 7 firing classes and illustrated in Table 6. Also, Burnability Index (BI) of the raw meals, calculated according to the following equation:

$$BI = \frac{\sum CaO\ free\ \%\ at\ (1350°C) + (1400°C) + (2x1450°C) + (3x1500°C)}{(\Delta CaO\ free\ \%\ at\ 1350°C - 1500°C)^{1/4}}\ x\ 3.73 \quad (1)$$

Table 6. BI values which are categorized into 7 firing classes

BI values	Firing classes
<60	Very easy
60- 80	Easy
80-100	Normal
100-120	Some hard
120-140	Hard
140-160	Very hard
> 160	Extremely hard

Table 7 indicates the burnability index values of different cement raw meal (CRM) containing C&D waste materials. Reference cement raw meal is defined as CRM0. The effect on the burnability was evaluated on the basis of the unreacted lime (free lime, CaO) content in samples sintered at the selected temperatures.

Table 7. Burnability test results of generated raw meals

Mixture	C&D Waste Content (%)	1350°C	1400°C	1450°C	1500°C	Burnability Index (BI)	Result
		Free CaO	Free CaO	Free CaO	Free CaO		
CRM0	0	8.3	6.8	2.7	1.9	61.4	Easy firing
CRM1	17.45	14.1	8.9	7.3	4.4	107.4	Some hard firing
CRM2	9.1	9.4	7.2	3.1	2.2	66.9	Easy firing
CRM3	15.72	9.2	6.9	3.1	2.1	65.4	Easy firing
CRM4	14.77	8.9	6.8	3	2.1	64.7	Easy firing
CRM5	25.81	9	7.1	2.9	2.0	64.0	Easy firing

It can be seen that, substitution of the Portland cement raw meal with the recycled C&D wastes deteriorates the burnability of the raw meals in relation to the reference (M0). C&D waste materials can cause burning difficulty in raw materials. A significant increase in free CaO content is noted for CRM1 modified cement raw meal.

B. Petrographic Examination

In general, petrographical examination of Portland cement clinker reveals a texture of large crystals of alite (C_3S, tricalcium silicate, Ca_3SiO_5) and belite (C_2S, dicalcium silicate, Ca_2SiO_4). Microstructural examination of polished and after HF etching surfaces are given in Fig 1-6.

Generally, clinker produced without using C&D waste materials exhibits homogenous belite (C_2S), alite (C_3S) and liquid phase distribution homogeneous and proper vacancy structure (Fig. 1). Alite appears in brown color after HF etching. C_3S crystals are approximately 25 µm sizes and homogeneous structure. In region 1, belite crystals are seen as small rounded blue color particles sizes ranging from 5 to 20 µm around the edges of large C_3S crystals. Liquid phases are appearing homogeneously between C_2S and C_3S crystals (Region 2).

Micrograph of clinker produced by using tile waste represents heterogeneous small size distribution of alite crystal (Region 3) and homogenously distributed liquid phase (Fig. 2).

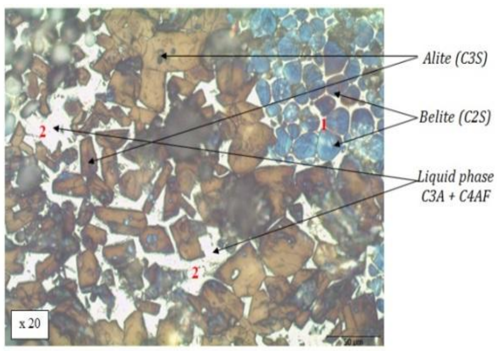

Fig.1. Clinker without C&D wastes

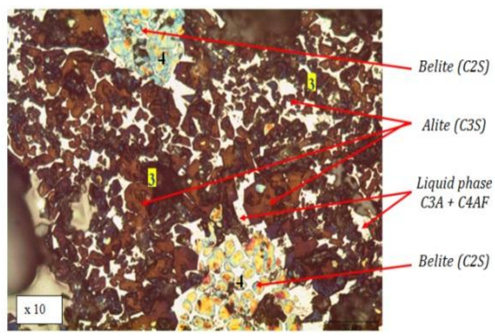

Fig.2. Clinker produced with tile waste

The amounts of alite crystals were found low with suitable size distribution clinker produced with fire brick waste. Contrary to this, belite crystals were found intensely. Generally, small amount liquid phase was observed (Fig. 3).

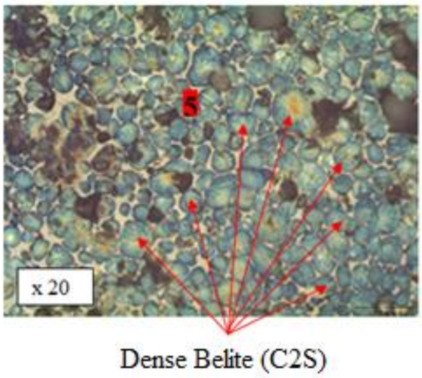

Fig.3. Clinker produced with fire brick waste

On the other hand, heterogeneous size distribution was seen at alite crystals of clinkers produced with brick waste (Fig. 4). In some regions dense belite crystals were detected. Low amount of alite and liquid phases were observed at clinkers produced with plaster waste (Fig. 5). Concrete waste using supplied suitable amount of liquid phase and low amount of alite phase (Fig. 6).

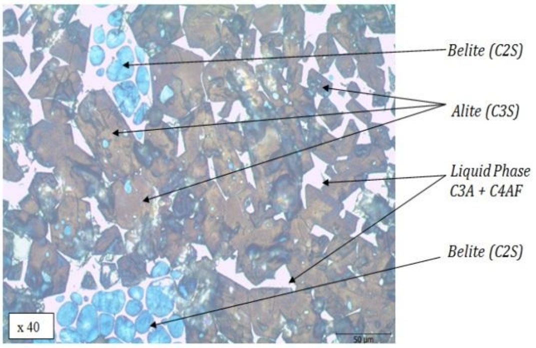

Fig.4. Clinker produced with brick waste

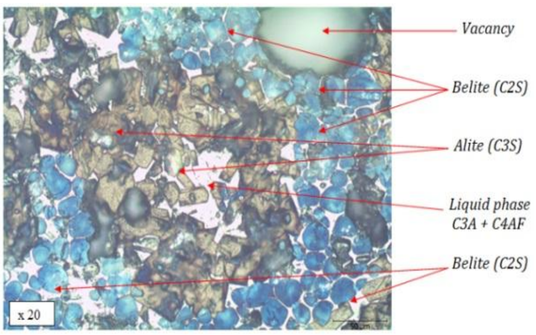

Fig.5. Clinker produced with plaster waste

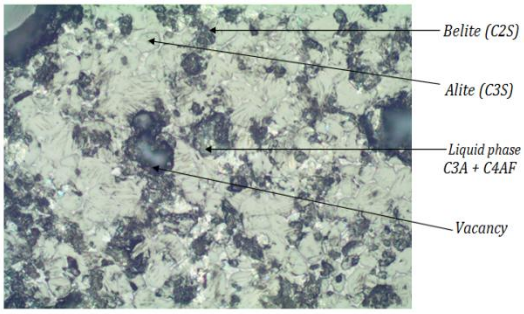

Fig.6. Clinker produced with concrete waste

Based on the laboratory scale results, an industrial scale cement production was conducted with using C&D waste addition. In industrial scale cement production, there are many parameters which affect the furnace regime and product quality like furnace temperature, flame intensity, gas flow, temperature change, blockage and material feeding content etc. Any changing on these parameters can highly affect the clinker structure.

For this reason, mix C&D wastes were used with lower addition ratio for industrial scale study: 1 wt. %, 2.1 wt. % and 3.9 wt. % with 0-25 mm grain size distribution. CEM I 42.5 R type cement was produced with C&D waste addition according to TS EN 197-1 standard requirements [17].

IV. RESULTS & DISCUSSION

As a result of low moisture content is a required property for cement production, C&D waste materials moisture content values were found feasible to use; while $CaCO_3$ contents of plastered and concrete wastes were measured to be higher than other waste materials.

Micrographs of clinker produced with C&D wastes showed that more belite (C_2S) phases occurred. Increasing in belite crystals and belite clusters results in burning and grinding difficulty, and negatively affects strength properties of the cement. When performance of clinker produced with C&D wastes was examined, it was seen that 2 days strength values provided positive results, 7 days strength values showed parallel results with original clinker and 28 days strength values decreased by 1.5 MPa lower than original clinker. Clinker cooling time also decreased according to waste material substitution. Unfavorableness was not observed at emission measurements and dangerousness analyses of clinker. However, CO_2 content parallelly increased with increasing of C&D waste usage.

Then, CEM I 42.5R type cement was produced with using 1 wt. %, 2.1 wt. % and 3.9 wt. % C&D waste additive clinker. Obtained cement products provided required and standard properties; however, strength and hydration heat values were found to be lower. To discover the effect on the concrete products, C30/37 type ready mixed concrete was produced with using this C&D waste additive cement. Concrete mixtures were filled in molds with size of 10x10x10 cm^3. Strength values of C&D waste additive concretes were also found to be lower than required values.

Finally, optimum C&D waste substation ratio was determined as 3.9 wt. %. Fig.7 shows that clinker produced with using C&D waste addition and Fig.8 illustrates the concrete produced with using C&D waste additive cement.

Fig.7. Clinker produced with using C&D waste addition

Fig.8. Concrete products with using C&D waste additive cement

V. CONCLUSION

In recent years, urban transformation process has gained importance especially in big cities where population is grown up and buildings are getting older. As a consequence of these renewal process, huge amount of construction and demolition (C&D) wastes occur and constitute one of the biggest environmental problems. The present study focuses on the utilization of the C&D waste materials which is occurred from urban transformation process in Istanbul, which is the one of the biggest city of Turkey. According to the statistics, it is estimated that 7,500,000 tons/year C&D waste materials are going to occur in Istanbul.

In this study, an investigation was carried out to evaluate C&D wastes in cement production. In this scope, different types of C&D wastes such as fire brick, brick, plaster, tile and concrete waste materials were selectively obtained and characterized according to cement raw materials physical and chemical properties. To utilize these wastes as secondary raw material in cement, different addition ratios were researched (1, 2.1 and 3.9 wt. %) at laboratory and industrial scale the study.

Required phases, like belite and alite, obtained at the micrographs of clinkers produced with C&D waste. However, densification of belite (C_2S) phases caused burning and grinding difficulty, thus the the strength of the cement was affected negatively.

At the end of the study, 3.9 wt. % mix C&D waste addition was determined as technically optimum substitution ratio in cement production. Technical properties of obtained products were found in the standard limit values.

ACKNOWLEDGMENT

This study was supported within “Construction and Demolition Wastes Recycling and Determination of Utilization Criteria” project. The authors wish to acknowledgement for the financial support to Republic of Turkey Ministry of Environment and Urbanization Directorate General of Infrastructure and Urban Transformation Services. Project coordinator is TUBITAK Marmara Research Centre. The contributor institutions are ISTAC Incorporated Company and AKCANSA Cement Industry and Trading Incorporated Company.

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