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Effect of crushed ceramic and basaltic pumice as fine aggregates on concrete mortars properties

Hanifi Binici *

Kahramanmaras Sutcu Imam University, Department of Civil Engineering, Kahramanmaras, 46100, Turkey

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Abstract

This study examines the suitability of ceramic industrial wastes and huge amounts of basaltic pumice as a possible substitute for conventional crushed fine aggregates. Experiments were carried out to determine abrasion resistance, chloride penetration depths and the compressive strengths of concrete with crushed ceramic waste and basaltic pumice fine aggregates and to compare them with those of conventional concretes. Test results indicated that ceramic wastes and basaltic pumice concretes had good workability. Furthermore, it was found that abrasion resistance of crushed ceramic (CC) and crushed basaltic pumice (CBP) concretes was lower than that of conventional concretes. Test results also showed that maximum abrasion rate was obtained from specimen control (Mo), while minimum abrasion rate is obtained from M3 (60% crushed ceramic concrete) specimens. Abrasion resistance was increased as the rate of fine CC was decreased. Abrasion resistance of concrete was strongly influenced by its compressive strengths and CC and crushed CBP content. The crushed ceramic addition percentage decreased as the chloride penetration depth increased. Results of this investigation showed that CC and CBP could be conveniently used for low abrasion and higher compressive strength concretes.

Keywords: Abrasion resistance; Compressive strength; Ceramic waste; Basaltic pumice

1. Introduction

It has been estimated that about 30% of daily production in the ceramic industry goes to waste. Ceramic waste, which is durable, hard and highly resistant to biological, chemical and physical degradation forces, is not recycled in any form at present. The rate of growth in waste has put pressure on the ceramic industries to find a solution for its disposal. Meanwhile, conventional crushed stone aggregate reserves are being depleted rapidly, particularly in some desert regions of the world [1]. Use of inorganic industrial residual products in making concrete will lead to sustainable concrete design and a greener environment [2]. The need to develop concrete with non-conventional aggregates is urgent for environmental as well as economic reasons. A review of earlier research showed that industrial as well as other wastes have been used in concrete-making to improve the properties of concrete and to reduce cost. Inclusion of recycled tyre rubber fibres in concrete was found to avoid the opening of cracks and increase energy absorption [3]. Structural light weight concrete has been produced using oil palm shells [4] and demolished masonry waste [5] as aggregates. An improvement in the modulus of elasticity of concrete was observed with partial replacement of crushed stone coarse aggregate by crushed vitrified soil aggregate [6]. Compressive strength was unchanged when ceramic waste was used to partially replace conventional crushed stone coarse aggregate [7].

Ceramic waste can be transformed into useful coarse aggregate. The properties of ceramic waste coarse aggregate are well within the range of the values of concrete-making aggregates. The properties of ceramic waste coarse aggregate concrete are not significantly different from those of conventional concrete [8]. The use of ceramic waste

* Tel.: +90 344 2191278; fax: +90 344 2191250.
E-mail address: hbinici@ksu.edu.tr.

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coarse aggregate concrete has increased because it has various advantages over other cementitious materials [9].

Almost 155,000 km^2 of the Turkey (country) is covered by Tertiary and Quaternary-age volcanic rocks, among which tuffs occupy important volumes [10]. Additives are used to improve the mechanical durability, workability and economy of concrete. The additives used in this study, basalt and GGBS, have been investigated for their properties previously [11].

Abrasion resistance of concrete, which is largely dependent on the hardness of the aggregate used, is of crucial importance in pavements, floors and hydraulic structures such as tunnels and dam spillways. Compressive strength and tensile strength are other vital factors controlling the abrasion resistance of concrete [12].

In this study, an attempt has been made to find out whether ceramic industrial wastes and large amounts of basaltic pumice are a suitable substitute for conventional crushed fine aggregate. The main objective of this investigation is to study the performance of concrete with ceramic waste and crushed basaltic pumice fine aggregate. Two sources of fine aggregate replacement were used in this work. Crushed ceramic and crushed basaltic pumice source were used at three levels of fine aggregate cement replacements (40%, 50%, and 60%). This study has been carried out mainly to investigate the abrasion resistance, the chloride penetration depth and the compressive strength of concrete.

2. Material and methods

2.1. Cement

The cement used was ASTM Type I normal Portland cement (PC 42.5 MPa) with a specific gravity of 3180 kg/m^3. Initial and final Vicat setting times of the cement were 115 and 200 min, respectively. Its Blaine specific surface area was 345 m^2/g and its chemical composition is given in Table 1.

2.2. Aggregate

Dry and clean natural river aggregate was used in concrete mixture. The gravel was 16 mm maximum nominal size. The physical properties of the river aggregates are given in Table 2. The grading of the river aggregate is presented in Fig. 1 with the standard limit [13]. These figures show that the aggregate grading is suitable for concrete production.

2.3. Crushed ceramic (CC)

Ceramic waste was supplied from Osmaniye in Turkey. Its chemical oxide composition is given in Table 1. Waste pieces are too big to be fed into a Los Angeles Abrasion Machine for crushing [14]. They are broken into small pieces of about 100–120 mm by a hammer and the surface is deglazed manually by chisel and hammer. Then small pieces are fed into a jaw crusher to achieve the required size of 4 mm or less. Physical properties of the CC are given in Table 3. The grading of the crushed ceramic fine aggregate

Table 2
Physical properties of the river aggregates

Property	Fine aggregate	Coarse aggregate
Specific gravity (kg/m^3)	2.65	2.7
Fineness modules	2.68	–
Water absorption 24 h (%)	0.75	1.24
Void (%)	46.20	44.25
Maximum size	4	16
Bulk density (kg/m^3)	1695	1627
Abrasion value (%)	–	26
Soundness test: weight loss after 30 cycles (%)	–	7.1

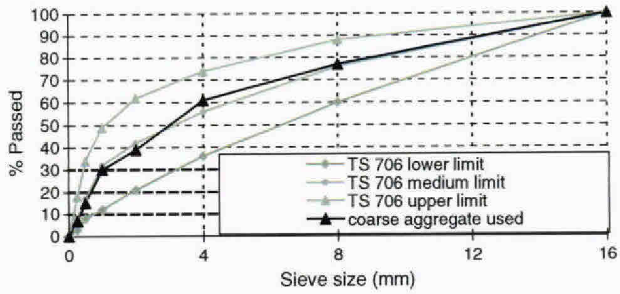

Fig. 1. Grain size distribution of coarse aggregates used in test specimens (as defined by sieving).

Table 1
Chemical and physical characteristics of materials used

Materials	Oxides (%)						
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI
PC 42.5	19.4	5.5	3.9	63.4	1.8	2.0	–
CC	88.4	7.3	0.5	0.1	0.1	–	0.4
CBP	63.9	15.6	6.3	2.3	2.1	3.2	1.6

Specific gravity (kg/m^3)	Specific surface (m^2/kg)	Fineness (retained on 90-μm sieve)	Vicat time of setting (min)		Compressive strength (MPa)		
			Initial	Final	3 day	7 day	28 day
3180	345	8.2	115	200	24.2	37.3	48.6

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Table 3
Physical properties of CC and CBP

Property	CC	CBP
Specific gravity (kg/m^3)	2.44	2.71
Fineness modules	2.68	3.46
Water absorption 24 h (%)	0.71	0.88
Void (%)	44.2	64.2
Maximum size	4	4
Bulk density (kg/m^3)	1395	1401
Abrasion value (%)	28	35
Soundness test: weight loss after 30 cycles (%)	4.2	7.1

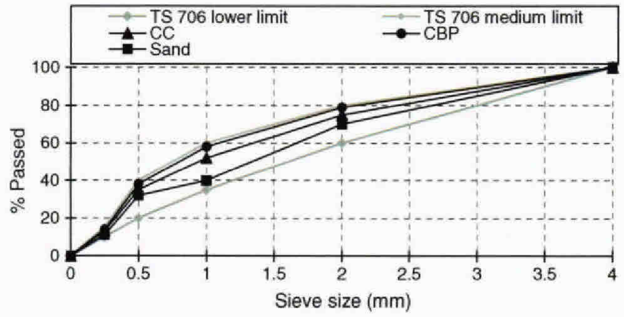

Fig. 2. Grain size distribution of fine aggregates used in test specimens (as defined by sieving).

is presented in Fig. 2 with the standard limit [13]. Fig. 2 shows that the fine aggregate grading is suitable for concrete production. Sand was replaced with crushed ceramic waste up to 40–60%.

2.4. Crushed basaltic pumice (CBP)

The basaltic pumice cone deposits of Quaternary age are located in the Cukurova region (Southern Turkey). There are estimated reserves of approximately 1000 million tonnes. The pumice comprises an average 85% volcanic glass and 15% phenocrystic feldspars, along with traces of spheroid hematite minerals, determined by microscopy. XRD tests show the presence of dominant illite and kaolinite as clay minerals along with feldspar. The high porosity and soft structure of the basaltic pumice promotes easy and economical crushing [15].

Physical properties of the CBP are given in Table 3. The grading of the crushed ceramic fine aggregate is presented in Fig. 2 with the standard limit [13]. Fig. 2 shows that the fine aggregate grading is suitable for concrete production. Also, sand was replaced with crushed basaltic pumice up to 40–60%.

2.5. Concrete mixture proportions

Approximate concrete composition is given in Table 4. The mixture is designed according to the absolute volume method given by Turkish Standard TS EN 802 [16]. At the beginning of the mixture design, binder content (400 kg/m^3) and water–cement ratio (0.48–0.51) were chosen as constant; then the volume of aggregate was determined for each control Portland cement concrete by assuming that 2% air is trapped in fresh concrete as suggested by TS EN 802. The volume of aggregate was used to determine the fine aggregate weight. CC and CBP concrete was produced by modifying normal Portland cement concrete. The modification was made by replacing sand with CC and CBP for a given ratio on mass basis. Superplasticier admixture was used at various amounts to maintain the workability of fresh concrete. The amount of hyper plasticizer is given in Table 4.

Three cubic samples 150 mm on each side were used for each test of compressive strength and curing conditions. Three cubic samples were cured at 75% RH, and three other cubic samples were cured in water after demoulding until testing at 28 days. Curing temperature was 20 °C. Compressive strength measurements were carried out using a hydraulic press with a capacity of 3000 kN; the loading rate was 0.3 MPa/s.

Table 4
Concrete mixture proportions

Properties	Mixture number						
	M0	M1	M2	M3	M4	M5	M6
Cement, C (kg/m^3)	400	400	400	400	400	400	400
CC (%)	0	40	50	60	0	0	0
CC (kg/m^3)	0	240	300	360	0	0	0
CBP (%)	0	0	0	0	40	50	60
CBP (kg/m^3)	0	0	0	0	240	300	360
Water, W (kg/m^3)	185	190	193	195	196	198	201
W/C	0.46	0.47	0.48	0.48	0.49	0.49	0.50
Sand SSD (kg/m^3)	600	360	300	240	360	300	240
Coarse aggregate (kg/m^3)	1200	1200	1200	1200	1200	1200	1200
Superplasticizer (l/m^3)	2.8	3.6	3.5	3.6	3.6	3.7	3.7
Slump (mm)	110	90	85	80	90	85	82
Air content (%)	2.2	2.3	2.2	2.1	2.4	2.3	2.1
Air temperature (°C)	28	27	28	26	27	28	27
Concrete temperature (°C)	29	28	29	26	27	28	29
Unit weight (kg/m^3)	2310	2319	2321	2325	2318	23123	2330

Abrasion testing was performed in accordance with Turkish Standard Specifications TS EN 3262 [17]. In this standard, abrasion testing is applied on specimens of size 150 mm × 150 mm × 50 mm at the ages of 28, 90 and 365 days. First, the concrete specimens were cleaned using a wire brush and kept 24 h in a water tank at 20 °C temperature. At the end of this period the specimens were taken out and wiped with a wet cloth. The specimens were surface dry saturated (SDS). Sand blasting pressure is 40 N/mm^2. The rate of flow of abrasive sand was 600 g/min. In the present study, the test was carried out at 20 °C temperature and 50% relative humidity. SDS specimens were weighed and the weight was denoted as W_1. Sand blasting was performed for 60 s, applied to at least eight different points. At the end of this process the specimens were kept in 20 °C water for 2 h. Then, they are wiped with a wet cloth. Finally, samples were weighed and the result was denoted W_2. Hence, $W = W_1 - W_2$ was found as the loss of mass.

In literature, a number of methods to evaluate the chloride penetration into concrete have been developed. Chloride penetration depths were reported on 100 × 200 mm cylindrical specimens after 110 wetting–drying cycles [18]. Also, the other study was reported that $AgNO_3$ solution with 0.3% concentration was sprayed on broken pieces after splitting [19]. In addition to theses methods, rapid chloride permeability, full immersion and partial immersion tests also were reported in literature. The full immersion test was performed by Chindaprasirt et al. [20]. In that study, the chloride penetration of concrete was tested with the procedures similar to the set-up explained [21] with the exception where 50 mm thick cut cylinders and 3% NaCl solution were used [22].

In this study, same method described in Ref. [22] was used and test performed after six months. Concrete cylinders were demoulded after a day and cured in water until the period of 26 days. After that they were sliced 50 mm thickness with the 50 mm ends discarded. The sliced cylinders were left to dry in laboratory condition for 24 h before application of epoxy coatings. All specimens were epoxy coated around the cylindrical surface and after being finished the processes then they were left in the laboratory for testing.

3. Results and discussion

3.1. Compressive strength

The compressive strength of concrete mixes made with and without CC and CBP was determined at 7, 28, 90 and 365 days of curing. The test results were given in Fig. 3. From the test results, it can be seen that the compressive strength of CC and CBP concrete mixes with 40%, 50% and 60% fine aggregate replacement with CC and CBP were higher than the control specimen (M0) at all ages. It is evident from Fig. 3 that compressive strength of all mixes continued to increase over one year. It can be

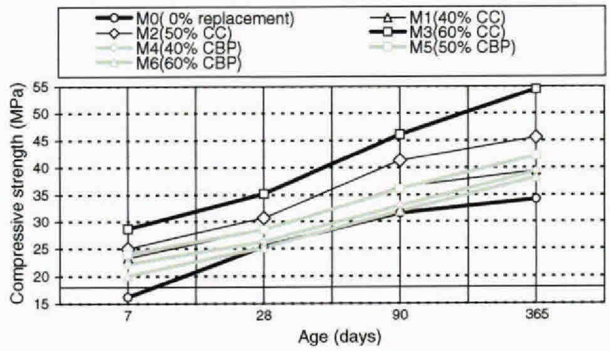

Fig. 3. Compressive strength of concrete mixtures versus age.

seen that there is an increase in strength with the increase in CC percentages; however, the rate of increase of strength decreases with the increase in CC content. Maximum strength at all ages occurred with 60% fine aggregate replacement. Fig. 3 shows the compressive strength at 365 days. Compressive strength development of control specimens was lower than CC and CBP concrete specimens at 365 days. CBP concrete specimens had slightly higher compressive strength than the M0 specimens.

Relative strength of tested concrete specimens was given in Fig. 4. In this figure, the ratio of 90 and 28 days compressive strengths of CC was very similar to the ratio of 365 and 28 days compressive strengths. In Fig. 4, it was observed that the ratio of 90 and 28 days compressive strengths of CBP specimens were lower than the ratio of 365 and 28 days compressive strengths of CBP specimens.

The relative strength (the ratio of the CC and CBP concrete to the strength of control specimens) of specimens in relation to curing age is given in Fig. 4. It can be observed from Fig. 4 that relative strength values of the CBP concrete specimens were lower than CC concrete at all ages. On the other hands, the relative strengths of the CC and CBP concrete specimens were higher; compared to those for control specimens. The development of the relative strengths of the CC and CBP concretes in relation to the curing ages was observed to be different. The relative strength ratio values for the CC and CBP concrete speci-

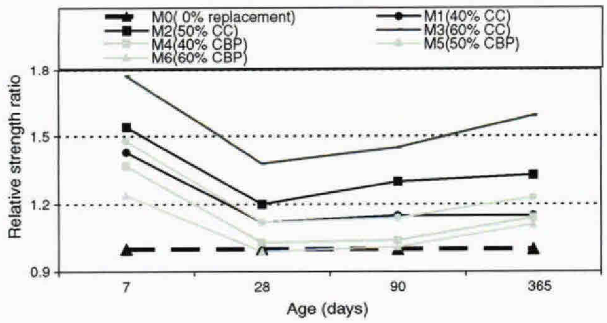

Fig. 4. Relative strength of tested concrete specimens.

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mens were lower than those for the control concretes. The highest compressive strengths at all ages were found in group M3. Considering early age average compressive strengths, the compressive strengths of group M1, M2 and M3 specimens were found to be 15%, 9% and 15% higher than that of group M4, M5 and M6 specimens, respectively (see Fig. 4). The effects of fine aggregate replacements on the compressive strengths of different groups were found to be different. Specimen M3 had the highest compressive strengths. The compressive strengths of specimens groups M2 and M3 were found to be higher, about 1.31 and 1.52 times that of M0 specimens, respectively. It can be seen from Fig. 3 that relative strength values of the CC and CBP concrete specimens were similar to control specimens at early ages. However, after 28 days especially CC specimens had higher relative strength values than the others.

It can be said that, the compressive strengths of the specimens made with crushed ceramic waste and basaltic pumice specimens were higher than those of the control at all tested ages. The strength development characteristics of the CC and CBP mortars were affected not only by the additive types, but in some cases, also by the replacement percentage of CC and CBP. Specimen M3 had the highest compressive strengths at all tested ages.

3.2. Abrasion resistance

Mass loss at 60 min of abrasion versus replacement with CC and CBP were given in Fig. 5. This figure show that the abrasion resistance of M0 specimens, without CC or CBP, was insufficient to resist the abrasion of concrete. Specimens with CC as fine aggregate were more suitable for abrasion resistance than either the M0 or CBP specimens. Use of higher percentages of CC would be superfluous. Mortars where CBP was used as a fine aggregate had enhanced abrasion resistance compared to control specimens. Mortar strength can be enhanced by adding either CC or CBP to the mix. However, the grain size distribution of the aggregate is an important feature in this process. Above all, the mortar specimen M1, M2, and M3 was proposed, with raw materials readily available in southern Turkey. The better abrasion resistance behavior of the mortars with the addition of fine crushed ceramic is believed to result from a denser pore structure of the mortar binder. The relation between pore structure, abrasion resistance and waterproofing is an ongoing topic of current research.

Abrasion ratio of specimens were given in Fig. 6. It can be said that from this figure, maximum abrasion rate was obtained from control specimens, while minimum abrasion rate was obtained from M3 specimens. Abrasion resistance is increased as the rate of fine CC and CBP was increased. However, over 50% and 60% basaltic pumice replacement levels, abrasion ratio and strength losses concrete were higher than 40% basaltic pumice specimen, respectively. There was no restriction about concrete abrasion ratio in Turkish standard. However, amount of concrete abrasions was lower than 1.2 mm was denoted high resistant abrasive concrete and amount of concrete abrasions is higher than 3 mm was indicated as poor resistant abrasive concrete [23].

Generally, the abrasion resistance of concrete can be improved by replacement as fine aggregates with crushed ceramics and crushed basaltic pumice (see Fig. 6). The abrasion resistance improved with increasing crushed ceramics. However, this not true for the all crushed basaltic pumice. Thus, both crushed ceramics and definite percentage crushed basaltic pumice concrete had higher compressive strength and lower abrasion ratio. This might be expressed to the fact that in crushed ceramic replacement allowed a good interfacial a condensed matrix.

3.3. Chloride penetration

Chloride penetration depths of the mixtures are given in Fig. 7. It can be seen from the figure that chloride penetration depth for CC 60% mixes was considerably less than those of other mixes. An increase in the percentage of additives from 40% to 60% reduced the chloride penetration depth significantly. Other additive types affected the chloride penetration depth slightly. Specimens with no additives (control specimens) show considerably greater chloride penetration depth.

The penetration depth was reduced with an increase in the CC and CBP percentage and an increase in the

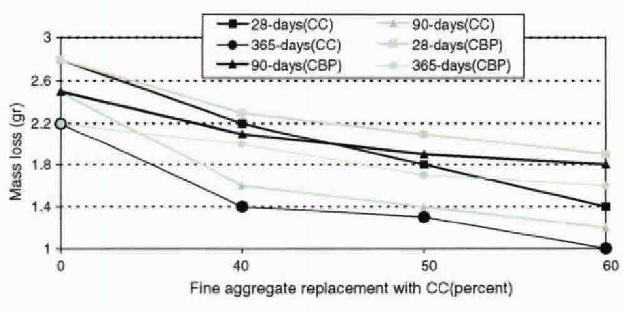

Fig. 5. Mass loss at 60 min of abrasion versus fine aggregate replacement with CC and CBP.

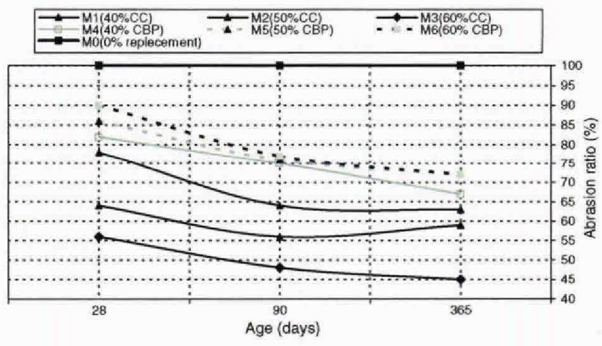

Fig. 6. Abrasion ratio of specimens.

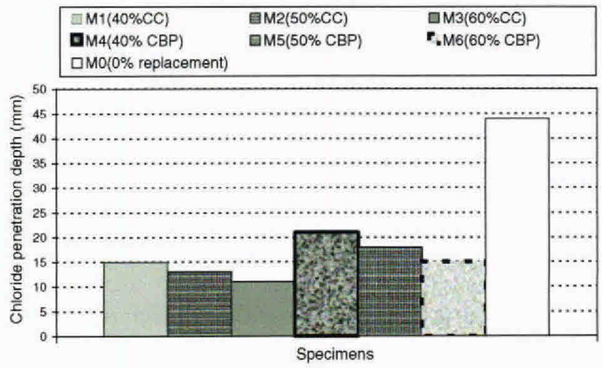

Fig. 7. Chloride penetration depth of all specimens.

compressive strength of the specimens. Results of the 6 months immersion test showed the general trend of the results as observed for the higher strength concrete specimens. Chindaprasirt et al. [20] reported that the method was good enough for the low and normal strength concretes where the difference in the chloride depth is large. The penetrations of the control concretes were lower than that of the CC and CBP concretes. This again indicated that the use of fine CC and CBP increased the chloride penetration resistance of concrete.

In general both crushed ceramics and crushed basaltic pumice had a profound effect on the chloride penetration depth. Also, as the crushed ceramic addition percentage decreased, chloride penetration depth increased (see Fig. 7). Test of chloride penetration depths correlated well with the additive type and replacement percentage of the mixtures. CC 60% specimens were significantly more resistant to chloride penetration than those of other specimens. An increase in the percentage of both CC and CBP additives also affected the chloride penetration depths sharply.

4. Conclusions

Based on the experimental results obtained from this study, the following conclusions can be drawn.

1. CC concrete group M3 specimens have higher compressive strength than the others.
2. Maximum abrasion rate is obtained from control specimens, while minimum abrasion rate was obtained from M3 specimens. Generally, abrasion resistance is increased as the rate of fine CC and CBP was increased. CC concrete had 30% lower abrasion than CBP concrete.
3. Abrasion resistance of concrete was strongly influenced by its compressive strength and CC and CBP content.
4. Measurement of chloride penetration depths correlated well with the differences between additive type and replacement percentage of the mixtures. CC 60% specimens were considerably more resistant to chloride ingress than those of other specimens. An increase in the percentage of both CC and CBP additives also affected the chloride penetration depths sharply.
5. Besides chloride penetration depths, the amount of chloride penetrated in CC 60% concretes was lower than that of control concretes, which is of great importance for the corrosion performance of embedded steel reinforcement in concrete.
6. Results of this investigation show that CC and CBP could be very conveniently used in concrete to achieve low abrasion and higher compressive strength concrete.

References

[1] Khaloo AR. Crushed tile coarse aggregate concrete. Cem Concr Aggregate 1995;17:119–25.
[2] Marianne Tange Jepsen, Dorthe Mathiesen, Christian Munch-Petersen, Dirch Bager. Durability of resource saving "Green" type of concrete. In: Proceedings of FIB – symposium on concrete and environment, Berlin, October 2001.
[3] Nehdi Monce, Khan Ashfaq. Cementitious composites containing recycled tire rubber: an overview of engineering properties and potential applications. Cem Concr Aggregate 2001;23:3–10.
[4] Basri HB, Mannan MA, Zain MFM. Concrete using waste oil palm shells as aggregate. Cem Concr Res 1999;29:619–22.
[5] Padmini AK, Ramamurthy K, Mathews MS. Behaviour of concrete with low-strength bricks as lightweight coarse aggregate. Mag Concr Res 2001;53:367–75.
[6] Palmquist Shane M, Jansen Daniel C, Swan Christopher W. Compressive behavior of concrete with vitrified soil aggregate. ASCE J Mater Civil Eng 2001;13:389–94.
[7] Devadas Manoharan P, Senthamarai RM. Concrete using ceramic insulator scrapas aggregate. In: Proceedings of the 6th international conference on Concrete Technology for developing countries, Amman, Jordan, October 2002.
[8] Senthamarai RM, Devadas Manoharan P. Concrete with ceramic waste aggregate. Cem Concr Compos 2005;27:910–3.
[9] Zhang YM, Napier TJ. Effects of particle size distributions surface area and chemical composition on Portland cement strength. Powder Tech 1995;83:245–52.
[10] Kaplan H, Binici H. Trass and trass cement. Cem World 1996;1:23–30 [in Turkish].
[11] Binici H, Aksogan O, Kaplan H. A study on cement mortars incorporating plain Portland cement (PPC) ground granulated blast-furnace slag (GGBS) and basaltic pumice. Ind Mater J 2005;12:214–20.
[12] Mindess S, Young JF. Concrete 671. USA: Prentice-Hall International; 1985.
[13] TS EN 706 Aggregate for concrete, Ankara, 1980 [in Turkish].
[14] TS EN 706 Abrasion for aggregate, Ankara, 1980 [in Turkish].
[15] Kelling G, Kapur S, Sakarya N, Akca E, Karaman C, Sakarya B, Robinson P. Basaltic Tephra: potential new resource for Ceramic Industry. Brit Ceram Trans 2000;99:129–36.
[16] TS EN 802 Design of concrete mixture. Ankara, 1985 [in Turkish].
[17] TS EN 3262-Test method for abrasion of concrete, 1978, Ankara, Turkey [in Turkish].
[18] Yigiter H, Yazici H, Aydin S. Effects of cement type water/cement ratio and cement content on sea water resistance of concrete. Build Environm, in press.
[19] Meck E, Sirivivatnanon V. Field indicator of chloride penetration depth. Cem Concr Res 2003;33:1113–7.
[20] Chindaprasirt P, Chotithanorm C, Cao H.T, Sirivivatnanon V, Influence of fly ash fineness on the chloride penetration of concrete. Construct Build Mater, in press.

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[21] Otsuki N, Nagataki S, Nakashita K. Evaluation of $AgNO_3$ solution spray method for measurement of chloride penetration into hardened cementitious matrix materials. Constr Build Mater 1993;7(4): 195–201.

[22] Meck E, Sirivivatnanon V. Field indicator of chloride penetration depth. Cem Concr Res 2003;33(8):1113–7.

[23] Postacioglu B, Concrete, vol. 2, Matbaa Teknisyenleri Basimevi, Istanbul, 1987 [in Turkish].