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Research Article

Assessing effects of waste coal bottom ash on construction cost of reinforced concrete structures considering experimental data

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ABSTRACT

In this study, it has been examined whether the bottom ash (BA) released to the nature as waste material from the thermal power plant can be used in reinforced concrete structures (RCS) and how much cost reduction will be caused in construction technology if BA is used in RCS. For this purpose, coal BA produced by Turkey-Zonguldak Cates power plant is mixed in different ratios into the concrete mixture of the beams. The different coal bottom ash ratio (BAR) is used instead of aggregate in the mixture. The beams created for 5 different BARs are subjected to tests and it is observed that the beam with the most critical bending is the beam with 75% coal BA. This BAR is applied to bearing elements of finite element model (FEM) and then current cost of the building and the construction cost used 75% coal BAR are compared with each other. It has been observed that when 75% coal BAR is used instead of aggregate in RCSs, there is a 40% reduction in construction costs. This result is of great importance both for the recycling of BA and for revealing that BA reduces construction costs.

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1. Introduction

Coal BA is the excellently distributed mineral residue resulting from the incineration of pulverized coal in power plants (PPs) and it is the major quantity of manufacturing leftover in the world. PPs every year, billion tons of coal BA are produced, and it is not recycled in the world. Therefore, coal BA produced in PPs all over our planet destroys our nature every year. Ensuring the recycling of this waste material is of great significance. Coal wastes burned in thermal PPs are transported with water and stored in ash dams. Toxic metals contained in coal ash might spread in the surrounding environment in case of waste leaking or explosion of the waste dams. Many studies have shown that living near coal ash disposal sites increases the risks of cancer and other diseases (Sönmez and Işık 2020). Although the chemical and physical belongings of coal ash make it ideal for a diversity of industrial presentations, it is supposed to compete with other inexpensive materials such as sand and gravel, so it is economical only when transportation and processing costs can be kept low. About three quarters of the coal ash produced in the United States is not recycled for commercial use, but instead is stored in specially designed, permitted dump areas (URL1). Twenty-four percent of the coal ashes obtained from thermal PPs in England is used as BA in lightweight concrete blocks (Aruntaş 2006; Güler et al. 2005; Huang et al. 2019; Hwang and Cortés 2021; Jang and Xing 2020). Additionally, Kaplan and Gültekin (2010) indicated many benefits of using coal waste in recycling in their research (Sönmez and Işık 2020). Many researchers have examined coal BA in the literature so far. Cao et al. (2008) examined utilization of BA from coal-fired PPs in China. It was indicated that the operation of PPs in China should improve to actual state-of-the- art. Careful input control, efficient burn out, and an additional feed of suitable components to improve a high quality of BA with low Loss on Ignition (LOI) will ensure higher standards in the utilization of Chinese BA. For the time being, the best chance is to replace solid clay bricks which become banned from 2007. Yost et al. (2013) examined structural performance of alkali acti-

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vated BA concrete. The procedures used in this investigation to create alkali activated BA concrete beams were effective in regards to material workability, strength, and stiffness, and conclusively show that BA can be practiced as a viable 100 % substitute for portland cement in the manufacturing of RC structural members. Wang et al. (2016) examined new technology and application of brick making with coal BA. The examination consequences offered that the different technology of brick creation could consume a large amount of BA. Varied amount of cement was simply 8–13%, and the cement rating was 425 #, the amount of BA additives in the composition was also minor, only 0.03–0.05%, for that reason, the charge of the project's creation was clearly lesser, and it exhibited decent financial profit for submission. Karalar (2020) performed experimental and numerical examination on flexural and crack failure of RC beams with BA and BA. In this study, load–deflection graphic for experimental test consequences is very parallel to load–deflection graphic of 3D numerical analyses. Additionally, actual near crack forms are found for experimental and numerical investigations. This obviously shows that FEM may be an exceptional alternative for damaging laboratory tests with conventional variations in the results. Ramachandran et al. investigated strong point and permanence behaviour of BA concrete in sea water surroundings related with normal and superplasticizer concrete. The pH, compressive strength, Half Cell Potential (HCP), Rapid Chloride Permeability Test (RCPT) and carbonation test showed better results in concrete with BA and superplasticizer (FA) (Ramachandran et al. 2017). Dinelli et al. (1996) performed experimental investigation on the use of BA for lightweight precast structural elements. The technical feasibility of the wide use of BA in fundamental concrete in the way of lightweight aggregates and as fine pozzolanic components has been presented by the tests available in this research. Wu et al. (2014) assessed characteristics of CFBC BA and properties of cement-based composites with CFBC BA and coal-fired BA. It was shown that CFBC BA has the potential as an alternative of cementing materials and as an alternative of pozzolan. The primary situation period rises with a growing amount of cement replacement by CFBC BA and coal-fire BA. The lower compressive strength has been gained in mortar with numerous mixtures of coal-fired BA and CFBC BA than the comparable ordinary Portland cement (OPC) mortar. Coal-fired BA can be successfully used in decreasing the length alteration. Nevertheless, CFBC BA would results in a higher length change when adding over 30%. Therefore, the quantity of CFBC BA replacement cement was suggested to be limited below 20%. Besides, there are many studies about coal BA in the literature such as Albitar et al. (2015), Baspinar (2014), Cavusoglu et al. (2021), Dry et al. (2004), Esquinas et al. (2018), Li et al. (2018), Nakamura et al. (2021), Sun et al. (2019), Tan et al. (2019), and Verma et al. (2019).

As realized from these studies, very few investigators were observed the effects of various coal BA ratios on construction cost of RC library buildings in the past. Besides, there are very few studies about the effects of various coal BA ratios on 3D seismic behaviour of library structural elements (beams, columns) in the literature. Therefore, in this study, it is intended to reveal the effects of coal BA contribution on the seismic behavior and construction cost of library structures.

2. Aim of the Study

In this study, to investigate the effects of various coal BA ratios on construction cost of RC buildings is investigated in detail. For this purpose, total 5 various RCBs are created in the research laboratory. Firstly, pure concrete is produced in laboratory. At that point BA is used instead of aggregate in pure concrete and BA added RC is obtained. The BARs used in pure concrete are 25%, 50%, 75% and 100%. Then, these beams are subjected to bending test. The most critical beam (concrete with 75% coal BA) is taken as reference and the properties of this reference concrete material is used for structural elements of a library building to investigate the effects of coal BARs on construction cost of RC buildings. For this purpose, the existing structure has been modeled with the mechanical belongings of the 75% BA substitution and the carrier system has been reanalyzed, except for the foundation system. Then, earthquake analysis has been performed. It is observed that the structure is not damaged in the earthquake when dimensions of the columns and beams in the structure used coal BA added concrete are reduced. Then, the cost has been compared between concrete with 75% BA substitution and without BA in the current design. From this result, it is concluded that when concrete with 75% coal BA is used in RCSs, there will be a significant reduction in the cost of RC library constructions and this recycling will make an important influence to the country's economy.

3. Preparation of RC Beams

In Zonguldak-Turkey, coal is produced since the 1900s and this produced coal is sent to both other provinces and countries. For this reason, a coal-fired thermal power plant (Çates) was established in Zonguldak to turn coal into energy. The waste coal BA produced in this coal-fired thermal power plant is released to nature every day and causes great damage to nature. Therefore, recycling of this coal BA is of great importance both for Turkey's economy and health of people living in located in the Zonguldak. In this study, the contribution of the addition of coal BA, which is waste in nature, to the construction cost of RCSs is investigated both experimentally and numerically. Experimentally, the concrete material is prepared in the laboratory and 0%, 25%, 50%, 75% and 100% coal BA is added instead of aggregate in the prepared concrete materials. As a result of this experiment, the most critical BAR is determined. Details of the concrete samples organized in the research test site are offered in Table 1. As can be realized from Table 1, sample 1 represents pure concrete and other samples represent additive concretes. Coal BA has been used in the concrete mix to replace aggregates of 0-5 mm grain size. Details of the materials used in 5 different concrete beams are presented in Table 2.

Table 1. Concrete samples for various BARs (Karalar 2020).

Sample Number	Statement
1	Pure concrete
2	25% BA
3	50% BA
4	75% BA
5	100% BA

Table 2. Components in the concrete examples and weight per unit of components (Karalar 2020).

Material	Pure	25% BA	50% BA	75% BA	100% BA
Cement (kg)	9.00	9.00	9.00	9.00	9.00
Water (kg)	4.77	4.77	4.77	4.77	4.77
BA (kg)	0.00	3.77	7.54	11.31	15.08
0-5 mm aggregate (kg)	23.14	17.35	11.57	5.78	0.00
5-15 mm aggregate (kg)	12.73	12.73	12.73	12.73	12.73
15-25 mm aggregate (kg)	21.99	21.99	21.99	21.99	21.99
Admixture material (kg)	0.12	0.12	0.12	0.12	0.12
Unit weight of concrete (kg)	71.75	69.74	67.72	65.71	63.69

When Table 2 is observed in detail, it is realized that there is no BA in pure concrete and the BA rates are gradually increased for other concrete samples. According to Table 2, the maximum BAR used in concrete materials instead of aggregate is 100% (15.0832 kg). Total 9 kg cement and 4.77 kg water is used in 5 different concrete materials. In addition, Limak CEM IV / B (P) 32.5 N / R pozzolanic cement is used for 5 different concrete materials. City water is used for the water in the concrete materials. Weber 10 water impermeable admixture is used as an additive to increase the consistency of the concrete. For the RC samples, BA is obtained from Zonguldak coal-fired thermal power plant and added to the concrete materials. The capacity of this coal-fired thermal power plant is 2x150 MW. About 1.500.000 tons of coal is burned annually in this factory. Conclusions, tons of ash are formed annually. 5 different concrete sample mixes are mixed in the concrete mixer and the concrete consistency is adjusted (Fig. 1).

After the concrete samples are prepared, they are subjected to slump test (Fig. 2). The slump test results of concrete samples with 5 different BARs are given in Fig. 3. While the experimental consequences are observed, it is determined that while BAR in the concrete sample increased, the slump values of the concrete increased. 4.9 cm slump value is obtained for pure concrete and 5.5 cm slump value is observed for 25% BA. This result shows the effect of BA on concrete consistency. In addition, 18.8 cm slump value is acquired for 50% BA and 25 cm slump value is observed for 75% BA. Finally, 4.1 cm slump value is obtained for concrete with 100% BA. It is clearly seen from these results that when the BAR used in concrete is increased from 0% to 75%, the consistency of concrete gradually increased. This result obviously shows the effect of BA on the consistency of the concrete material (Karalar 2020).

Fig. 2 shows that how concrete beams and beam molds are prepared in the laboratory. 5 different RC beam molds are prepared in a private laboratory. The dimensions of the 5 different beam molds are equal and the beam mold dimensions are 300x400x2000 mm. Total 10 different stirrups are used in concrete beams and the distances between stirrups are 200 mm. Besides, the diameter of stirrups is 8 mm. 2 compression reinforcements are placed on the concrete beams to ensure stirrup connections. These compression reinforcement bars have a diameter of 12 mm. In addition, 3 tension reinforcements are placed at the bottom of the beam molds and the diameter of these tension bars is 12 mm. In Figs. 3 and 4, pouring concrete materials into beam molds and performing vibration process are shown in detail. After a total of 5 different beams are prepared in the laboratory, a total of 28 days are waited for the concrete to reach the desired hardness, and after 28 days, the beam molds are removed (Fig. 4) (Karalar 2020).



Fig. 1. Preparation of concrete material in the laboratory.



Fig. 2. Preparation of molds for concrete beams (Karalar 2020).



Fig. 3. Pouring the concrete material into the beam molds and performing the vibration process (Karalar 2020).



Fig. 4. View of prepared concrete beams (Karalar 2020).

4. Experimental Test Set-up and Results

In this division, the test set-up is shown in Fig.5 (Karalar 2020). 5 different RCBs prepared in the special laboratory are placed in the flexure-crack device shown in Fig. 6 and subjected to flexure and crack tests. Flexure and crack test results are offered in Fig. 7. The crack results of the beam prepared with pure concrete are shown in Figs. 7a and 7b. According to Figs. 7a and 7b, the maximum crack width for pure concrete is 3.17 cm. Besides, the maximum crack length for pure concreted beam is 43 cm. In Figs. 7c and 7d, the flexure and crack test results of the beam prepared by adding 25% coal BA into concrete instead of aggregate are presented. According to Figs. 7c and 7d, maximum crack width is 2.68 cm and maximum crack length is 39 cm. From this result, it is seen that when coal BA is added to the concrete, the crack width and crack length decrease. In Figs 7e and 7f, flexure and crack test results of the beam prepared by adding 50% coal BA into concrete instead of aggregate are shown in detail. According to Figs. 7e and 7f, the maximum crack width on the beam is 2.05 cm and the maximum crack length is 32 cm. In Figs. 7g and 7h, test results of the beam prepared by adding 75% coal BA to the aggregate in the concrete are presented. If 75% of coal BA is added instead of aggregate in the concrete inside the beam, the maximum crack width is 1.66 cm and the maximum crack length is 24 cm. Finally, for the beam where 100% coal BA is used instead of the aggregate in the concrete, the maximum crack width is 2.19 cm and the maximum crack length is 31 cm (Figs. 7i and 7j). It is clear from these results that the most critical threshold value for 5 different coal BARs (0%, 25%, 50%, 75%, 100%) used instead of aggregate in concrete is 75% coal BAR. If this ratio is used instead of aggregate in concrete, it causes the smallest crack width and crack length in beam elements. From this result, it is concluded that using 75% coal BAR in RCSs may cause less damage in the RC structures (Karalar 2020).

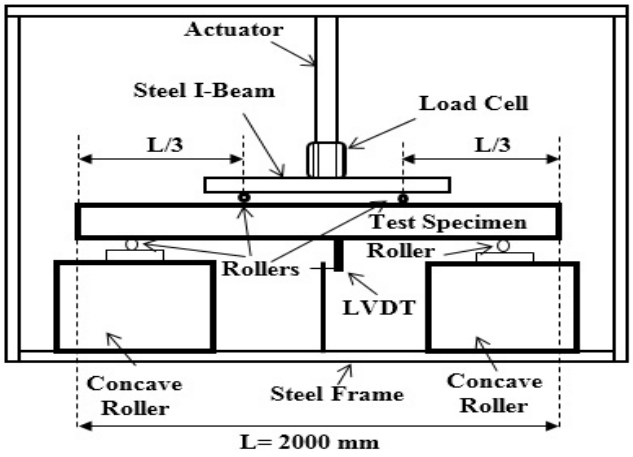


Fig. 5. Loading configuration for static testing (Karalar et al. 2020).

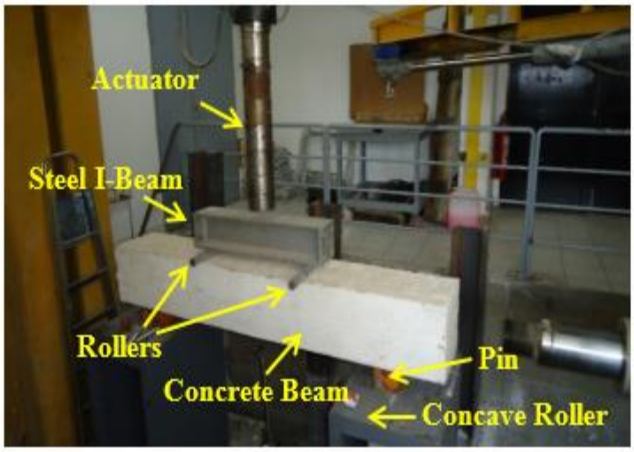


Fig. 6. Static testing apparatus (Karalar et al. 2020).

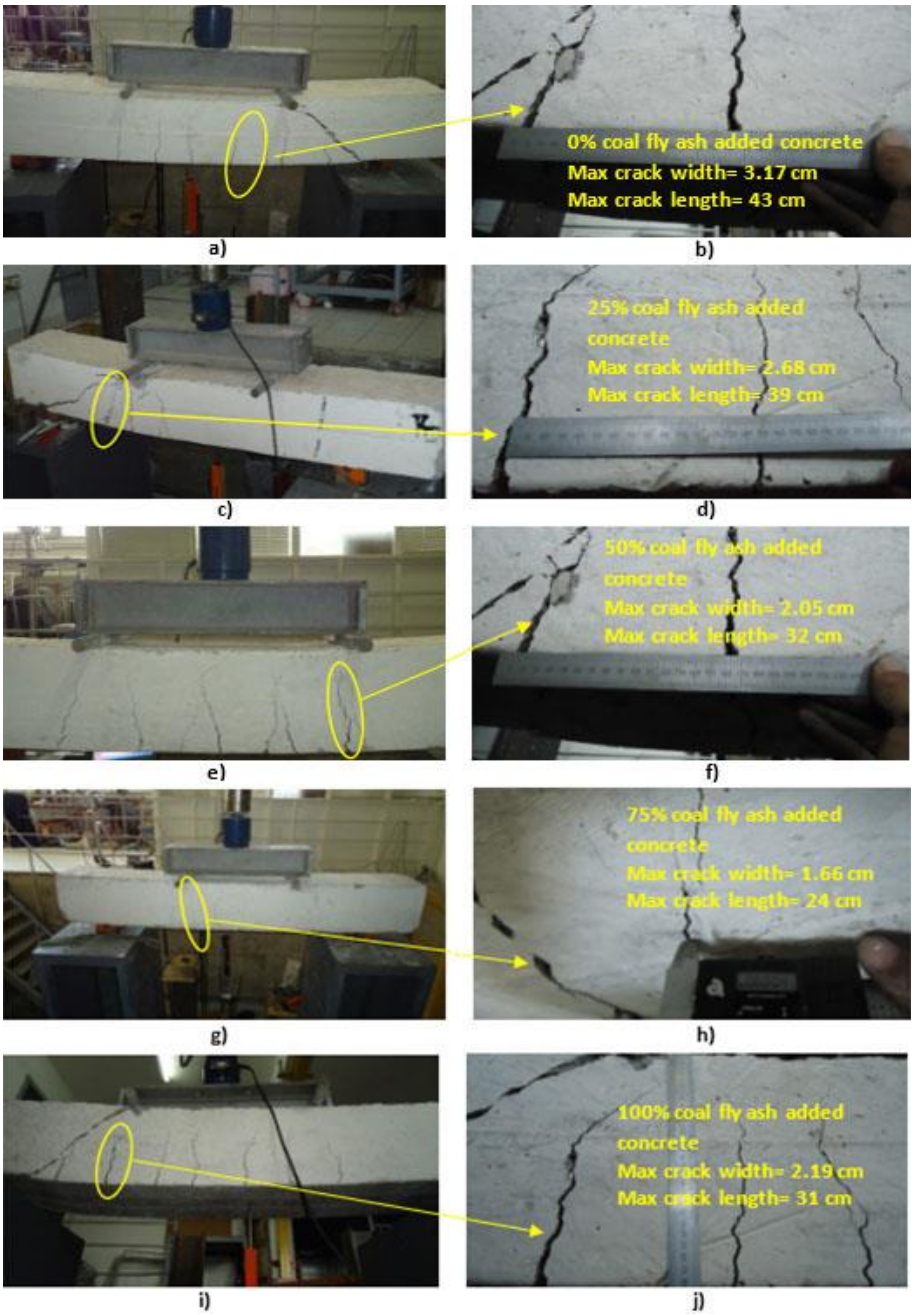


Fig. 7. Crack test results of 5 different beams (Karalar 2020).

5. 3D Modelling RC Building and Earthquake Analysis Results

Library structures are one of the important structures that people use frequently. Hundreds of people enter and exit the library structures every day. Controlling the seismic safety of these structures is of great importance for the safety and health of people. Therefore, library structure is used for numerical analysis in this study. In this part, it is intended to observe whether the building will survive under different ground motions and various coal BARs in the concrete material. For this purpose, firstly, current situation of library building is modelled according to original building project. 4 five multi-story RC building is chosen for 3D modelling and SAP2000 is developed whereas demonstrating of this RC building. Whereas demonstrating this RC building, 6 dissimilar columns are demarcated to the SAP2000 and thickness-elevation of these columns are demarcated as 70x70 cm, 60x60 cm, 50x50 cm, respectively (Fig. 8). Furthermore, there is a spherical column in the building and its diameter is demarcated as 50 cm. Then, width-height of beams used in the SAP2000 is demarcated as 40x70 cm, 35x70 cm, 30x70 cm, 40x60 cm, 40x50 cm, 30x50 cm, respectively (Fig. 8). Class of concrete are demarcated as C35 and this rate is gotten from original structure project. Overall sight of library construction is presented in Fig. 9.

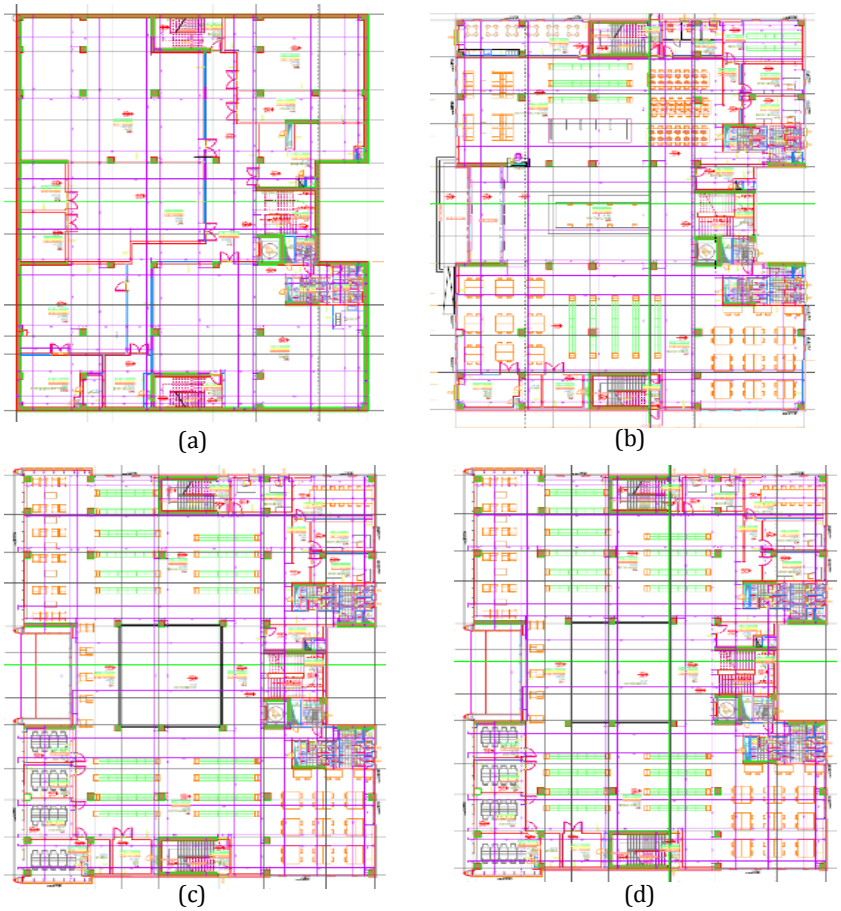
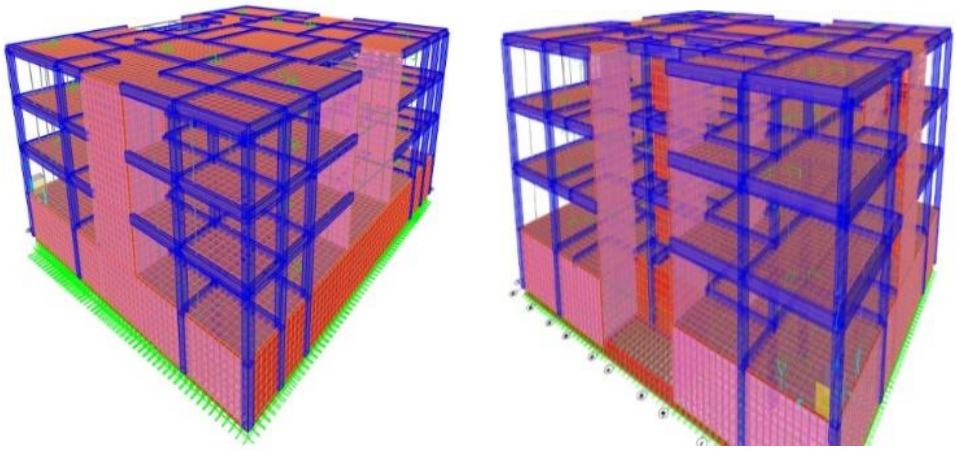


Fig. 8. Divisions of building levels: a) First level; b) Second level; c) Third level; d) Fourth level.



Fig. 9. General view of library building.

In the library RC building, there are entirely 2 dissimilar shear walls and their thicknesses are 20 cm and 25 cm. Moreover, thickness of ground layer is taken as 20 cm for all floors. Altitude of separately ground is taken as 3 m and there are completely 4 floors in the building. Additionally, inflexible diaphragms are formed in the building allowing for restraint z axis. At that point, nonlinear time history analyses are done allowing directing incorporation result type. Thus, Hilber-Hughes-Taylor method is chosen in the analyses and its gamma and beta value is chosen as 0.5 and 0.25, respectively. 3D model of building is presented in Fig. 10. Earthquake accelerations of 10 various earthquakes are used in 3D earthquake analyses. Mechanical properties of various earthquakes are presented in Table 3.



(a) (b)

Fig. 10. 3D model of library building: a) Right view; b) Left view.

Table 3. Mechanical properties of various earthquakes.

Earthquake Record Station	*d* (km)	PGA	PGV	Ap/Vp	TPV	TP
1999 Chi-Chi Earthquake 1	17.8	0.17	59	2.83	6.5	6.0
1999 Chi-Chi Earthquake 2	18.1	0.25	46	5.33	1.4	1.3
1979 Imperial Valley Earthquake 1	0.5	0.30	91	3.23	3.0	3.1
1979 Imperial Valley Earthquake 2	0.6	0.46	109	4.14	3.2	3.8
1979 Imperial Valley Earthquake 3	1.0	0.38	91	4.10	3.4	3.9
1995 Kobe Earthquake	0.6	0.60	74	7.95	0.8	1.4
1989 Loma Prieta Earthquake	5.1	0.48	45	10.46	0.8	0.7
1986 North Palm Spring Earthquake	8.2	0.59	73	7.93	1.1	1.4
1994 Northridge Earthquake 1	7.1	0.45	93	4.75	2.0	3.2
1994 Northridge Earthquake 2	7.1	0.33	67	4.83	1.8	1.9

3D earthquake analysis outcomes are offered in Table 4. While Table 4 is observed, the earthquake analysis consequences for the current situation of RC library structure and the earthquake analysis results for the coal BA added situation of RC structure are presented separately. 3D earthquake analyses are performed under 10 different earthquakes. Damages in the building were evaluated by examining the stresses and displacements that occurred in the beams and columns in the building after the earthquake analyses. According to 10 different earthquake analysis results, no damage is obtained in the structural elements for the current situation of the building. From this result, it is established that the existing bearing columns and beams are sized appropriately for these earthquakes. Besides, provided that the dimensions of the existing bearing elements of the structure remain constant, it has been observed that if 75% of the coal BA is added to the aggregate in the bearing elements of the structure, no damage will occur for 10 different earthquakes. When the size of the columns and beams is reduced by 10% ratio for the structure with coal BA, there is no damage to the building for 10 different earthquakes. No damage is observed in the structure for 10 different earthquakes in the case of reducing the dimensions of the carrier elements by 20%, 30%, 40% ratios for the structure with coal BA. However, if the dimensions of the bearing elements for the coal BA added structure are reduced by 50% ratio, the structure is damaged for 1999 Chi-Chi earthquake, 1989 Loma Prieta earthquake, 1986 North Palm earthquake, 1994 Northridge earthquake. In this case, it is concluded that the reduction ratio that should be taken as reference is 40% ratio. From this result, it is concluded that if 75% ratio of coal BA is used instead of aggregate in the library structures, the carrying ele-

ments of the structure can be reduced by 40% ratio, and if the carrier elements are reduced by 40% ratio, the structure may resist earthquakes. It is understood from this result that if 75% ratio of coal BA waste material is used in concrete material of RC structures, it will cause a significant decrease in the cost of the building.

Table 4. Earthquake analysis results for current situation and coal BA added situation.

Earthquake	Current situation of structure	Reduction ratio for structural elements (beams and columns)					
		10%	20%	30%	40%	50%	60%
1999 Chi-Chi Earthquake 1	+	+	+	+	+	-	-
1999 Chi-Chi Earthquake 2	+	+	+	+	+	-	-
1979 Imperial Valley Earthquake 1	+	+	+	+	+	+	-
1979 Imperial Valley Earthquake 2	+	+	+	+	+	+	-
1979 Imperial Valley Earthquake 3	+	+	+	+	+	+	-
1995 Kobe Earthquake	+	+	+	+	+	+	-
1989 Loma Prieta Earthquake	+	+	+	+	+	-	-
1986 North Palm Spring Earthquake	+	+	+	+	+	-	-
1994 Northridge Earthquake 1	+	+	+	+	+	-	-
1994 Northridge Earthquake 2	+	+	+	+	+	+	-

6. The Effect of Using 75% Coal BA in Concrete on Construction Costs

Depending on the use of coal in the thermal PPs in Turkey as realized in Table 5, about 108 million tons of waste was generated between the years 2010 through 2018; 94.37% of this consists of ash, slag, BA and gypsum and 70.44% of the waste was sent to ash mountains, ash dams or regular disposal sites. In 2018 alone, 26.1 million tons of waste was generated from 55 thermal PPs and 14 thousand tons of which was classified as hazardous; while 87.5% of the total waste was disposed in ash mountains, ash dams or disposal sites, 12.4% of which was sent to licensed waste treatment facilities and used for backfilling of mines and quarries. Most of the coal waste was disposed in the ash mountains, ash dams or disposal sites URL2, URL3, URL4, URL5, URL6, URL7.

Table 5. Waste statistics of thermal PPs in Turkey.

All running thermal PPs with 100 megawatts (MW) or more		Years				
		2010	2012	2014	2016	2018
The number of thermal power plants		51	59	66	61	55
The amount of non-hazardous waste (ton)		N/A	N/A	24,182,316	19,464,946	26,113,329
The amount of hazardous waste (ton)		N/A	N/A	9,100	11,979	13,805
The amount of total waste (ton)		18,747,759	19,262,185	24,191,416	19,476,925	26,127,134
Disposing (ton)	Disposed in the ash mountains/ash dams	12,186,043	12,982,713	11,684,454	16,224,279	22,861,242
	Landfill	6,561,716	3,679,077	5,249,537		
	Others			3,628,712	3,252,646	26,127
	Sold or sent to licensed waste disposal and recycling companies		2,600,395	3,628,712		3,239,765
N/A: Not available						

The use of BA in concrete rises the compressive strength of concrete as well as the resistance of concrete against abrasion (Aruntaş 2006, Kaplan and Gültekin 2010). Adding 20-30% ash into cement in the construction of concrete roads also reduces the cost of road construction (Kaplan and Gültekin 2010). BA can be partially used in concrete mixtures as a cement substitute, for example this ratio may be 35% or 25% of the cement amount and BA contributes to concrete compressive strength. By using BA, less electrical energy will be used for cement production and so energy savings will be achieved. Since BA is a very thin material, it increases the

workability of concrete as well Arıoğlu and Manzak (1992). The Ministry of Environment and Urbanization of Turkey states that in accordance with the general technical specification for construction, there should be a minimum of 250 kg/m^3 cement and 50 kg/m^3 BA to be used in the roller compacted concrete mixture. Additionally, according to the general technical specifications for RC works, it is recommended that mineral additives such as BA should not exceed 30% of the cement amount in order not to deteriorate the permeability property of concrete (Directorate of High Technics Board, 2018). The analyses and unit fees available by the Ministry of Environment and Urbanization of Turkey were used for cost comparisons. For transportation calculations, sand, gravel and cement are brought from the closest mine and factory to the construction site at a distance of 45 km and 164.5 km (Tables 6 and 7). The BA is brought from the Catalagzi Thermal Power Plant at a distance of 12 km (Table 8), which is also assumed that it will be taken free of charge. Table 9 and 10 show the approximate unit costs of one cubic meter of concrete prepared using 100% sand and one cubic meter of concrete prepared using 25% sand and 75% BA, respectively. In the case of using 75% BA in concrete with the current design, the cost comparison is made in Table 11 and the cost comparison between the current design and the more economic design is made in Table 12. The transport formulas (Tables 6-8) were taken from the Ministry of Environment and Urbanization of Turkey. Sand and gravel are brought from Caycuma District that is the closest mine to the construction site, and the density of sand or gravel is taken into account in calculations as 1.6 tons/m^3 to convert ton to m^3.

Table 6. Transportation of 1 m^3 of sand and gravel to the construction site.

Name of analysis: Sand or crushed stone transportation (m^3)					
Item no	Definition	Unit of measure	Quantity	Unit price	Amount ($)
19.100.2495	F = A x K x (0.0007 x M+0.01) x G				4.21
A	Difficulty coefficient		1.00		
G	Density of sand and crushed stone	ton/m^3	1.60		
10.110.1003	K: Motor vehicle carriage coefficient	$	63.33		
M	Transportation distance	km	45.00		
15.100.1002*	Loading, unloading and storing of material.	m^3	0.80	0.563	0.45
*If the material is available on the construction site 80% of the transportation cost will be paid.					
				Transportation and labor cost:	4.66

Table 7. Transportation of 1 ton of cement to the construction site.

Name of analysis: Cement transportation (ton)					
Item no	Definition	Unit of measure	Quantity	Unit price	Amount ($)
19.100.2495	F = A x K x (0.0007 x M+0.01)				7.93
A	Difficulty coefficient		1.00		
10.110.1003	K: Motor vehicle carriage coefficient	$	63.33		
M	Transportation distance	km	164.50		
15.100.1001*	Loading, unloading and stowing of any type of cement	ton	0.50	2.813	1.41
*Half of the unit price will be deducted as the cost of loading at the factory.					
				Transportation and labor cost:	9.33

Table 8. Transportation of 1 m^3 of BA to the construction site.

Name of analysis: BA transportation (m^3)					
Item no	Definition	Unit of measure	Quantity	Unit price	Amount ($)
19.100.2495	F = A x K x (0.0007 x M+0.01) x G				1.63
A	Difficulty coefficient		1.00		
G	Density of BA	ton/m^3	1.40		
10.110.1003	K: Motor vehicle carriage coefficient	$	63.33		
M	Transportation distance	km	12.00		
15.100.1002*	Loading, unloading and storing of material.	m^3	0.80	0.5633	0.45
*Eighty percent of the unit price will be paid as no storing at the construction site					
				Transportation and labor cost:	2.08

Cement is brought from city of Bolu that is the closest cement factory to the construction site and the density of cement is not taken into account in the calculation because no conversion is needed. BA is brought from Catalagzi Thermal Power Plant and the density of BA is taken into account in calculations as 1.4 tons/m^3.

Unit prices of plant-mixed concrete in Tables 9 and 10 were calculated using the construction unit prices and analyses of the Ministry of Environment and Urbanization of Turkey. The calculated unit prices show approximate market prices and may vary.

In the case of the current design shown in Table 11, a price comparison was made when using 100% sand and using 25% sand-75% BA in ready-mixed concrete. The difference is not significant when the cost of disposal and pollution to nature are not considered. The difference is occurred from that the BA is assumed to be taken free of charge, and the transportation distance is approximately one quarter of the sand transportation distance.

It is seen in Table 12 that the difference increases significantly when 75% of the BA is used in the calculation when considering the mechanical properties of the BA.

Table 9. Unit price of 1m^3 of C25/30 plant-mixed concrete with 100% sand.

Item no	Definition	Unit of measure	Quantity	Unit price	Amount ($)
	Material (C25/30 cement mortar):				
10.130.1026	Sand	m^3	0.5000	4.27	2.14
	Sand transportation	m^3	0.5000	4.66	2.33
10.130.1029	Crushed stone (up to 32 mm)	m^3	0.7100	6.56	4.66
	Crushed stone transportation	m^3	0.7100	4.66	3.31
10.130.1204	Portland cement (bulk)	ton	0.3750	38.67	14.50
	Portland cement transportation	ton	0.3750	9.33	3.50
10.130.9991	Water	m^3	0.1550	1.47	0.23
	Labor:				
	Pumping and pouring:				
19.100.1059	Automatic concrete plant (1000 L capacity, 50 m3/hour) hourly rate	h	0.0200	7.55	0.15
10.100.1015	Concrete master	h	0.3000	3.08	0.92
10.100.1063	Expert laborer	h	0.3000	2.40	0.72
10.100.1051	Driver	h	0.6000	3.13	1.88
10.100.1055	Machine operator	h	0.6000	3.61	2.17
10.100.1057	Assistant operator	h	0.6000	2.96	1.78
10.160.1026	Diesel fuel	kg	1.4250	1.08	1.54
10.160.1030	Electric power	kWh	8.7500	0.13	1.11
10.100.1062	Unskilled construction worker	h	5.0000	2.25	11.25
	Compacting and protecting:				
19.100.1033	Concrete vibrator hourly rate	h	0.3125	4.88	1.52
10.130.9991	Water (for curing)	m^3	0.5000	1.47	0.73
10.100.1015	Concrete master	h	0.9375	3.08	2.88
	Sampling and laboratory tests:				
10.100.1060	Foreman	h	0.3125	4.52	1.41
10.100.1062	Unskilled construction worker	h	0.3125	2.25	0.70
				Material and labor cost:	59.42
				25% contractor's profit and overheads:	14.86
				Price per m^3:	74.28

Table 10. Unit price of 1m³ of C25/30 plant-mixed concrete with 25% sand and 75% BA.

Item no	Definition	Unit of measure	Quantity	Unit price	Amount ($)
	Material (C25/30 cement mortar):				
10.130.1026	Sand	m³	0.5*0.25	4.27	0.53
	Sand transportation	m³	0.5000	0.5*0.25	4.66
N/A	BA (75% substitution for sand)	m³	0.5*0.75	0.00	0.00
	BA transportation	m³	0.7100	0.5*0.75	2.08
10.130.1029	Crushed stone (up to 32 mm)	m³	0.7100	6.56	4.66
	Crushed stone transportation	m³	0.7100	0.7100	4.66
10.130.1204	Portland cement (bulk)	ton	0.3750	38.67	14.50
	Portland cement transportation	ton	0.3750	0.3750	9.33
10.130.9991	Water	m³	0.1550	1.47	0.23
	Labor:				
	Pumping and pouring:				
19.100.1059	Automatic concrete plant (1000 L capacity, 50 m3/hour) hourly rate	h	0.0200	7.55	0.15
10.100.1015	Concrete master	h	0.3000	3.08	0.92
10.100.1063	Expert laborer	h	0.3000	2.40	0.72
10.100.1051	Driver	h	0.6000	3.13	1.88
10.100.1055	Machine operator	h	0.6000	3.61	2.17
10.100.1057	Assistant operator	h	0.6000	2.96	1.78
10.160.1026	Diesel fuel	kg	1.4250	1.08	1.54
10.160.1030	Electric power	kWh	8.7500	0.13	1.11
10.100.1062	Unskilled construction worker	h	5.0000	2.25	11.25
	Compacting and protecting:				
19.100.1033	Concrete vibrator hourly rate	h	0.3125	4.88	1.52
10.130.9991	Water (for curing)	m³	0.5000	1.47	0.73
10.100.1015	Concrete master	h	0.9375	3.08	2.88
	Sampling and laboratory tests:				
10.100.1060	Foreman	h	0.3125	4.52	1.41
10.100.1062	Unskilled construction worker	h	0.3125	2.25	0.70
				Material and labor cost:	56.86
				25% contractor's profit and overheads:	14.21
				Price per m³:	71.07

Table 11. Cost comparison in case of using 75% BA in concrete with the current design.

Type	Section		Total length	Concrete volume	Concrete with 100% sand	Concrete with 75% BA
	m	m	m	m³	($/m³)	($/m³)
Column	0.60	0.60	486.00	174.960		
Column	0.70	0.70	108.00	52.920		
Beam	0.30	0.70	1074.77	225.702		
Beam	0.25	0.70	31.20	5.460	$74.280	$71.071
Beam	0.60	0.70	249.16	104.647		
Beam	0.50	0.70	154.00	53.900		
Beam	0.40	0.70	128.37	35.944		
Total				653.533	$48.544	$46.447
Difference					$2.097	

Table 12. Cost comparison between the current design and the more economic design.

Type	Section		Total length	Concrete volume	Concrete with 75% BA
	m	m	m	m^3	($/$m^3$)
Column	0.35	0.35	486.00	59.535	$71.071
Column	0.40	0.40	108.00	17.280	
Beam	0.25	0.40	635.80	63.580	
Beam	0.25	0.40	31.20	3.120	
Beam	0.30	0.50	238.36	35.754	
Beam	0.30	0.50	141.40	21.210	
Beam	0.30	0.50	103.97	15.596	
Beam	0.40	0.60	442.12	106.109	
Beam	0.40	0.60	33.85	8.124	
Beam	0.40	0.60	10.80	2.592	
			Total	332.899	$23.660
			Difference (48,544-23,660)		$24.884

7. Conclusions

In this study, it has been investigated whether the BA released to the nature as waste material from the thermal power plant can be used in RCSs and how much cost reduction will be caused in construction technology when BA is used in RCSs. In the current design, the cost of concrete used only in beams and columns was calculated as $48,544, and the cost of concrete with 75% BA substitution in concrete was $46,447. The difference was $2,097.

- If the building had been designed considering the mechanical properties of the BA, then the cost difference would have been $24,884. If the foundation of the building is also reanalyzed according to the more economical dimensions, it is obvious that this cost difference will increase even more.
- According to the ready-mixed concrete producers in Zonguldak, it has been stated that approximately 250-300 thousand cubic meters of ready-mixed concrete is used annually in Zonguldak Center, Kozlu and Kilimli Districts. For example, if BA is used in 100 thousand cubic meters of yearly produced ready-mixed concrete, approximately 37,500 cubic meters of BA (100,000*0.375 = 37,500) will be used and the cost difference will be 37,500*($59.42-$56.86) =$96,000.
- Turkey produced 67 million cubic meters of ready-mixed concrete in 2019 according to Turkish Ready-Mixed Concrete Association and according to Turkey Statistical Institute in the year of 2018 data URL2, 22,861,242 cubic meters of coal waste from PPs was disposed. If BA had been used in approximately 10 million cubic meters of concrete, 3.75 million cubic meters of BA would have been used and the cost difference would have been $9,600,000.
- In addition, the use of BA in concrete will significantly reduce the cost of getting rid of the BA and the possible damages to the environment will be prevented.

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