

The effect of fly ash content and types of aggregates on the properties of pre-fabricated concrete interlocking blocks (PCIBs)

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ABSTRACT

We studied the influence of fly ash content and replacement of crushed sand stone aggregate with concrete wastes and marble wastes in pre-fabricated concrete interlocking blocks (PCIBs). We have compared properties of PCIBs with fly ash produced with three different replacement ratios of aggregate. Compressive strength, tensile splitting strength, density, apparent porosity, water absorption by weight, abrasion resistance, alkali-silica reaction and freeze-thaw resistance of PCIBs were determined. When comparing the PCIBs with crushed sand stone, the replacement of crushed sand stone with concrete waste and marble waste results in lower physical and mechanical properties. By contrast, replacement of cement with fly ash (from 10% to 20%) has a significant effect in increasing important properties of PCIBs.

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1. Introduction

USA, Belgium, France, Spain, Sweden, Italy, Egypt, Portugal, Brazil and Greece are among the countries with considerable marble reserves. Turkey has even more, 40% of total marble reserves in the world. Seven million tons of marble are produced in Turkey annually. In processing marble such as cutting to size and polishing for decorative purposes, marble dust and aggregate are created as byproducts. More specifically, during the cutting process 20–30% of the marble block turns into dust. Thus, waste materials from marble processing plants represent millions of tons [1]. 1400 tons of waste marble per day are left and stored on depot areas as wastes in Turkey [2]. Saboya et al. [3] reported that the amount of waste from cutting and sawing process in Brazilian decorative stone industries can easily reaches 20–25% of the total volume of the block. Hebhou et al. [4] reported that a high volume of marble production has generated a considerable amount of waste materials; almost 70% of this mineral gets wasted in the mining, processing and polishing stages with obvious impact on the environment.

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A huge quantity of construction waste is produced every day, representing a large fraction of the total solid waste stream all over the world. Construction waste is mainly composed of concrete waste. Eguchi et al. [5] reported that construction industry produces about 20% concrete waste of total industrial waste in Japan. Marinkovic et al. [6] reported that about 850 million tons of concrete waste is generated in the countries of European Union per year, what represent 31% of the total waste generation. In North America, construction waste and demolition makes up about 25–45% of the waste stream, depending on the region [7].

Fly ash, a by-product of coal power plants, causes environmental pollution while the cost of storage of fly ash is very high. In Turkey, the annual fly ash production is about 18 million tons more than the rest of all industrial waste in the country [8]. In India, approximately 80 million tons of fly ash is generated each year [9]. The current annual production of fly ash worldwide is estimated around 600 million tones [10].

Overall, a very high amount of waste is being produced all around the world. The most common method of managing waste is through its disposal in landfills creating in that way huge deposits of waste. In this situation, waste recycling is gaining increasing importance [11]. Also, restricted laws in the form of prohibitions or special taxes for creating waste areas have been brought into practice. It seems that stricter future waste disposal regulations may be applied because the disposal of the waste has

become a severe social and environmental problem. Recycling has the potential to reduce the amount of waste put into landfills and to preserve natural resources. Recycling, one of the strategies in minimizing waste, offers three benefits: (i) reduces the demand for new resources; (ii) cuts down on transport and production energy costs; (iii) utilizes waste which would otherwise be lost to landfill sites [12].

Concrete remains an indispensable construction material and allows engineers to evaluate many materials by incorporating them into concrete. Thus, the use of waste materials, industrial wastes in the production of concrete is growing in importance [13]. The use of fly ash in concrete is both economical and modifies the properties of concrete in both the fresh and hardened states, providing improvements to workability, strength and abrasion resistance [14,15].

A number of studies have been performed by using recycled aggregate in concrete, but they always resulted in a lower level of concrete strengths [16,17]. The quality of recycled concrete aggregates is usually lower than the quality of natural aggregate. When demolished concrete is crushed, a certain amount of mortar and cement paste from original concrete remains attached to stone particles in recycled aggregate. This attached mortar is the main reason for lower quality of recycled concrete aggregates compared to natural aggregate [6].

Alyamac and Ince [1] as well as Topcu et al. [2] studied the feasibility of using waste marble dust as a filler in self-compacting concrete (SCC). They reported that marble dust had no effect on workability of SCC. Mechanical properties of SCC have become somewhat worse using marble dust. Terzi and Karasahin [18] investigated the use of marble dust in asphalt mixtures as filler. They have concluded that marble waste in dust form could be used in such cases. However, little is known on the influence of marble waste as aggregate in concrete paving blocks on the properties of those blocks. Recently concrete block pavements have become an attractive engineering and economical alternative to both flexible and rigid pavements. The strength, durability and aesthetically pleasing surfaces have made paving blocks attractive for many commercial, municipal and industrial applications such as parking areas, pedestrian walks, traffic intersections, container yards and roads.

Our above survey shows that there was no study on utilization of marble waste in fabrication of concrete paving blocks. Therefore, purpose of our work was determination of feasibility of using marble waste, concrete waste and fly ash in fabrication of concrete paving blocks and effects of waste marble on physical, mechanical and durability properties of concrete paving blocks.

2. Experimental

2.1. Materials

2.1.1. Cement

Ordinary Portland Cement (OPC) type of CEM I 42.5R complying with TS EN 197-1 [19] was used. The cement was commercially available in Turkey. The specific gravity of cement used was 3.07. Initial and final setting times of the OPC were 300 and 530 min, respectively. The Blaine specific surface area was 3210 cm²/g.

2.1.2. Aggregates

Mainly two groups of aggregate were used in the production of PCIBs, fine and coarse. Coarse aggregate was crushed limestone in size of 6/12 mm with specific gravity of 2.71. That coarse aggregate was used in all the types of PCIBs. Fine aggregates were marble waste, concrete waste and crushed sand stone. All of them had the size of 0/4 mm. Waste marble and concretes were prepared as an aggregate by crushing and grinding in a laboratory mill, then sorting via sieves into two groups of coarse (>4 mm) and fine (<4 mm) aggregates. Gradation of aggregates and mixture was presented in Table 1. The specific gravity of the fine crushed sand stone (CSS), marble waste (MW) and concrete waste (CW) aggregates was 2.65, 2.70 and 2.24, respectively.

Table 1
Particle distribution aggregates and mixture.

Aggregates	Sieve size (mm)						
	12	8	4	2	1	0.5	0.25
Fine aggregate	100	100	83.4	60.4	34.26	16.86	8.06
Coarse aggregate	100	67.7	0	0	0	0	0
Mixture	100	80.6	33.5	24.2	13.7	6.7	3.2

Table 2
The physical and chemical properties of materials.

	OPC	Fly Ash	CW	CSS	MW
<i>Chemical properties</i>					
CaO	63.6	6.7	36.0	51.4	51.8
SiO ₂	19.3	47.4	28.0	2.9	4.7
Al ₂ O ₃	5.6	19.8	3.9	1.1	–
Fe ₂ O ₃	3.5	11.8	2.10	0.2	0.03
MgO	0.86	4.76	1.48	1.0	0.4
SO ₃	2.96	1.86	–	0.03	–
K ₂ O	0.8	2.62	1.29	0.14	–
Na ₂ O	0.13	0.57	0.26	0.03	–
LOI	1.15	2.76	26.3	42.9	41.16
<i>Physical properties</i>					
Specific gravity	3.07	1.99	2.35	2.72	2.70
Fineness (Blaine) (cm ² /g)	3212	3126	–	–	–

2.1.3. Fly ash

The fly ash was supplied from Tunçbilek, Kütahya/Turkey Thermal Power. FA for use as additives in cement concrete has been classified in ASTM C 618 [20]. Specification into two general types: class C and class F. The three major oxides (SiO₂ + Al₂O₃ + Fe₂O₃) must be in total more than 50% for class C and more than 70% for class F. The fly ash was classified as F type according to the ASTM criterion, since the total of the major oxides in the fly ash is 79%. The Blaine fineness, which is defined as a measure of the particle size or fineness of cement and supplementary cementitious materials, was 3226 cm²/g. Specific gravity was 1.99 g/cm³. Its chemical composition was given in Table 2.

2.2. Mix design

Our work was divided into two parts. The first part aimed at the determination of the effects of fly ash content on the properties of blocks prepared with different types of aggregates. The second part aimed to evaluate the influence of the type of aggregates on the properties of the PCIBs. Totally, 15 series of concrete interlocking pavement blocks were prepared with fly ash content of 0%, 10%, 20%, 30% and 40% by replacement ratio of OPC by weight, and with three different types of fine aggregates, namely crushed sand stone, marble waste and concrete waste. The constituents of the PCIB mix were proportioned to achieve maximum packing of the particles and thus minimum of voids. Water to binder ratio was 0.45 in all the series. The binder content was kept as 300 kg/m³. The aggregate content of the specimens consisted as 40% coarse and 60% fine aggregate. The composition of the mixes is presented in Table 3.

2.3. Fabrication of PCIB

A 50 l batch was prepared for all mortar mixtures using a pan. The mixing sequence consisted of homogenizing the coarse and fine aggregates and binder for 1 min dry, and then adding water to the mixing container. The concrete mixture was mixed for 3 min. Then blocks were fabricated in steel molds using a dry-mixing method which simulates the actual industrial production process of concrete blocks. In other words, the mixes were prepared with water only sufficient to produce a cohesive mix but with no slump/workability. The size of PCIB specimens is shown schematically in Fig. 1. The mixes were prepared in a small factory machine using pressure (in ratio of 20%) and vibration simultaneously until complete compaction was obtained (Fig. 2a). The blocks were demolded immediately afterwards (Fig. 2b) and cured in laboratory conditions at 20 ± 2 °C and relative humidity of 65%. The PCIB specimens were wetted in the first 7 days. Then, they were air-cured until testing days.

2.4. Test methods

Several tests were conducted to determine the splitting strength, compressive strength, density, water absorption by weight, specific porosity, abrasion resistance, alkali silica reaction and freezing–thawing resistance of the PCIB. All the results below are the average of three specimens.

Table 3
Materials content for per cubic meter.

Series	Fly ash ratio (%)	Materials (kg/m ³)						
		Cement	Fly ash	Water	Fine aggregates			Coarse aggregate
					CSS	CW	MW	
M1	0	300	0	135	1212	–	–	826
M2	10	270	30	135	1205	–	–	822
M3	20	240	60	135	1198	–	–	817
M4	30	210	90	135	1191	–	–	812
M5	40	180	120	135	1184	–	–	808
M6	0	300	0	135	–	1024	–	826
M7	10	270	30	135	–	1018	–	822
M8	20	240	60	135	–	1013	–	817
M9	30	210	90	135	–	1007	–	812
M10	40	180	120	135	–	1001	–	808
M11	0	300	0	135	–	–	1235	826
M12	10	270	30	135	–	–	1228	822
M13	20	240	60	135	–	–	1221	817
M14	30	210	90	135	–	–	1214	812
M15	40	180	120	135	–	–	1207	808

CSS: Crushed sand stone; CW: concrete wastes; MW: marble wastes.

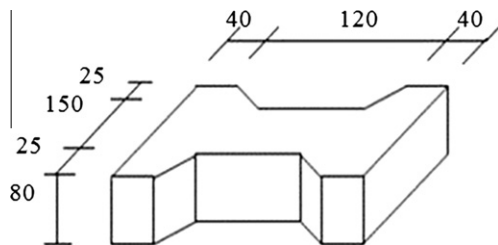


Fig. 1. Schematic representation of PCIB (measurements are in mm).

The compressive strength and splitting tensile strength were defined according to TS EN 12390-3 [21] and TS 2824 EN 1338 [22] standards, respectively, by 2000 kN compressive machine with a rate of loading controller. The compressive strength was tested on specimens aged 28 days; however, splitting tensile strength of PCIBs was tested on specimens aged 3, 7 and 28 days. The load was applied to the nominal area of paving blocks. The compressive strength was calculated by dividing the failure load by the loading area of the PCIB.

Density, specific porosity and water absorption were determined on the produced paving blocks aged 28 days according to Archimedes principle by the weight measurements of saturated specimens in air and in water, and dry weight (oven drying at 105 °C to constant weight).

The alkali silica reaction test were performed on the bars in the size of 25 × 25 × 285 mm according to ASTM C 1260 [23]. Mortar mixtures were prepared with fine aggregates and binder to determine the alkali silica reaction. The binder to aggregate ratio was 1/2.25. A fixed water to binder ratio of 0.50 was utilized for all mixes. The specimens were de-molded after 24 h, and the first length measurements were performed on the specimens by using the displacement gage with

0.01 mm. Then, the second length measurements were made after the specimens were cured in pure-water at 80 °C for 24 h. The bars were then stored in 1 M sodium hydroxide (NaOH) solution at 80 °C. The expansion of the mortar bars were measured at 3, 6, 9, 12 and 14 days aged bar specimens.

PCIB specimens were subjected to abrasion testing at 28 days after casting according to TS 2824 EN 1338 standard. Before testing, specimens were dried in an oven at 105 ± 5 °C until reaching a constant weight. An abrasion test apparatus used is shown in Fig. 3a. 142.5 N loads were applied to the specimens in the abrasion system. The length and diameter of disk was 70 and 200 mm, respectively. In the test procedure, 1 l of corundum-crystalline powder was flowed between the disc and the specimen from powder box (Fig. 3b), and the disc was rotated with a rotational velocity of 75 rpm for 1 min for each specimen. After that, the length loss due to wear was measured from the three points on the specimens, and the averages of these measurements were determined for each specimen (Fig. 4).

For the freeze–thaw testing, the PCIBs were exposed to ASTM C666 Procedure A [24] conditions: the specimens were kept in fully saturated condition with temperature cycling between –17 and +20 °C, each cycle took 6 h. The climatic chamber used consisted of cooling and heating equipment producing continuous freeze–thaw cycles with chamber temperatures ranging from –20 °C to +20 °C. The specimens were frozen for 1 h in air at –17 °C, and then they were immersed into the water for thaw for 2 h at +20 °C. 60 freeze–thaw cycles were performed on each PCIBs.

3. Results and discussions

3.1. Compressive strength

The effects of cement replacement with fly ash and the effects of different types of fine aggregate on compressive strength of PCIB

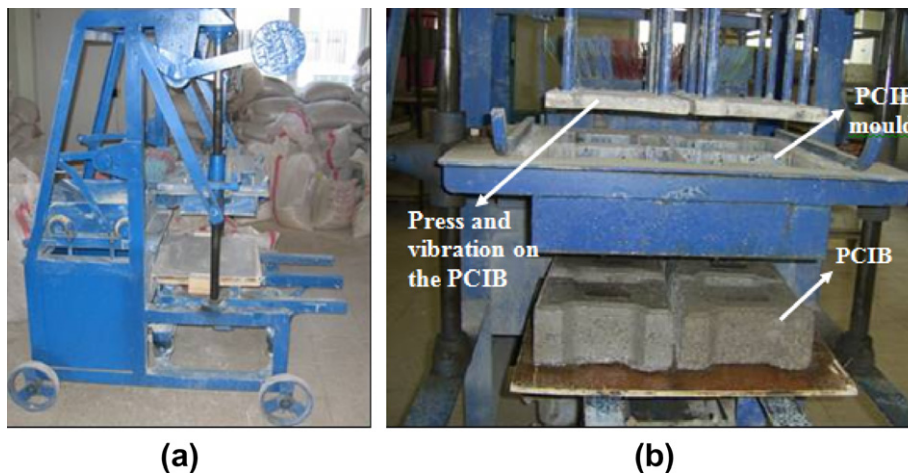


Fig. 2. A small factory machine (a) and production of PCIB specimens (b).

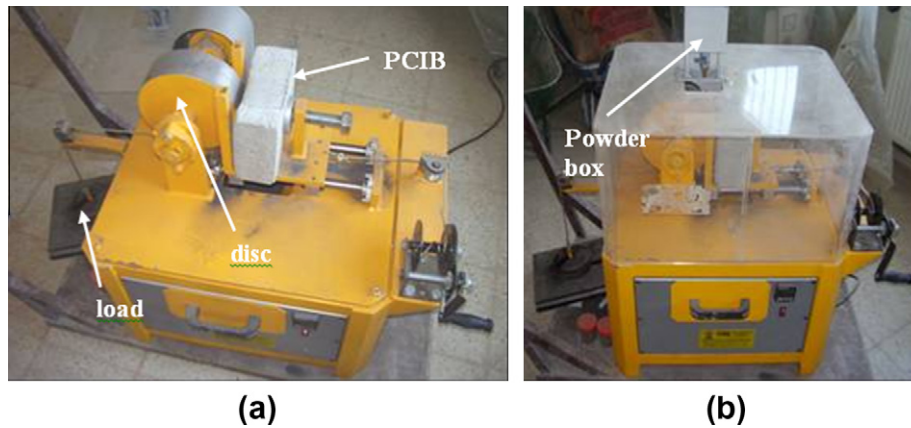


Fig. 3. Abrasion machine (a and b).



Fig. 4. Measuring of abrasion length of PCIB specimen.

are presented in Fig. 5. The compressive strength decreases as the fly ash replacement ratio for each series is increased, clearly so above 10%. Moreover, replacement of CSS with CW and MW results in a decrease of compressive strength in PCIBs. Aggregate has a significant influence on the strength properties of concrete pavement blocks. The influence of strength properties of pavement blocks increases with increasing density of aggregate. In addition to strength properties, all other properties of pavement blocks are also controlled by properties of the aggregate. The reduction in compressive strength is related to the weakness and surface texture of fine aggregates. We see that a replacement of CSS aggregates with recycled aggregates result in lower compressive strength. When the compressive strength of PCIB with CSS varied between 32.1 and 17.7 MPa, the compressive strength varied between 29.6 and 14.6 MPa and between 27.8 and 17.1 MPa for the PCIB series with CW and MW, respectively, depending on the fly ash replacement ratio. In general, the highest compressive strength is obtained in PCIBs with CSS. The lowest compressive strength is seen in the PCIBs with CW. Poon et al. [16] and Barra de Oliveira and Vasquez [25] reported that the saturation level of the recycled aggregates (CW) may affect the strength of the concretes since at higher saturation levels the mechanical bonding between the cement paste and the recycled aggregates becomes weaker. The decrease in compressive strength of PCIB was 0%, 17.9%, 15.7%, 43% and 16.54%, respectively, by replacing the fine CSS with fine CW aggregate depending on fly ash replacement ratio from 0% to 40%. However,

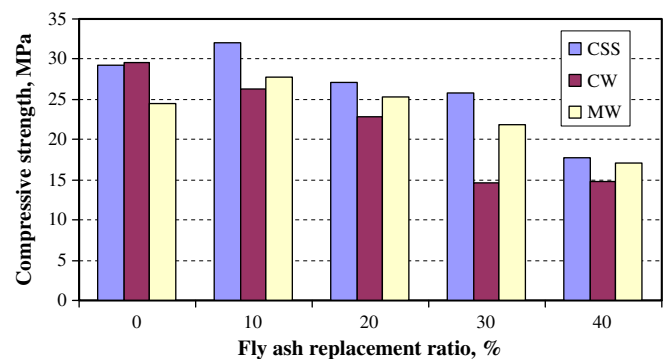


Fig. 5. Comparison of compressive strength of PCIBs versus fly ash content.

by replacing the fine CSS with fine MW aggregate, the decrease in compressive strength of PCIBs was 17%, 13.4%, 6.7%, 14.84% and 3.3%, respectively, depending on fly ash replacement ratio from 0% to 40%. Evangelista and Brito [26] studied the use of fine recycled concrete aggregates as partial or full replacements of natural fine aggregates in structural concrete. The experimental results indicated that the compressive strength went down by 10% as a result of the fine aggregate replacement ratio of 100%. Strength of pavement blocks are usually evaluated with tensile splitting strength values.

It is well known that for a given replacement level with mineral admixtures, the properties of concrete are influenced by the reactivity of the mineral admixtures [27]. When comparing the PCIB with CSS that contain no fly ash, an increase in the compressive strength due to the 10% fly ash content was 8.7%; however, the increase in compressive strength of PCIB with MW was 12% and 3.21% for fly ash content of 10% and 20%, respectively. On the other hand, the decrease in the compressive strength due to the 20%, 30% and 40% fly ash content was 7.57%, 12.2% and 39.5% when fine CSS aggregate was used in the production of PCIBs. The reduction in compressive strength of PCIB with CW ranged between 11% and 50.5% for fly ash content of from 10% to 40% while the reduction in compressive strength of PCIB with MW ranged between 10.5% and 30% for the fly ash replacement ratio from 30% to 40%. Salem and Burdette [28] found that the 28-day compressive strength, using 14% and 28% fly ash, of recycled concrete decreased from 38.85 to 35.5 MPa (9% reduction) and of natural concrete decreased from 38.1 to 34.1 MPa (11% reduction). Therefore, based on the results of this study, the optimum percent of added FA to enhance the compressive strength is 10%.

3.2. Splitting strength

Values of splitting tensile strength of PCIBs containing the CSS, CW and MW aggregates are presented in Figs. 6–8 showing the results for 3, 7 and 28 days. Though the PCIBs possess the lowest strength in early ages, they have a satisfactory strength enhancement rate with increase of curing time. We find that splitting strength of PCIBs with all type of fine aggregate increases with the age of pavement blocks, regardless of fly ash content. The range of strength increase of PCIBs with CSS, CW and MW, respectively, varies from 55.6% to 68.8%, from 43.7% to 43.3% and from 31% to 51%, depending on fly ash content, when increasing the age from 3 to 28. The results vary between 51.8% and 50%, between 36.7% and 33%, and 27.4% for the PCIB series with CSS, CW and MW, respectively, when increasing the concrete age from 7 to 28, depending fly ash replacement ratio. The strength development of PCIBs containing the CW and MW was higher than that of PCIBs with CSS at 3 and 7 days.

As mentioned before, the strength of pavement blocks are usually evaluated with tensile splitting strength values in Turkish standards. For paving blocks, a type of paving block for footway use is specified by standard (TS 2824 EN 1338) [22] in Turkey, requiring a 28-day characteristic splitting strength of 3.6 MPa. The characteristic splitting strength of PCIBs was compared in Fig. 9 depending on fly ash content from 0% to 40%.

3.3. Density

The density of values of our block specimens are presented in Fig. 10. For three PCIB types, density decreases with increase of fly ash replacement ratio with cement in the mixture. This can be attributed to the lower specific gravity of fly ash when compared to the specific gravity of cement. Differences between CSS and MW are not significant. However, when the density of CW is compared to those of PCIB with CSS and MW, density of PCIB with CW is highly lower. The control paving blocks have the highest density compared to the contaminated paving blocks. In general, the contaminated paving blocks showed an average 5% decrease in density. Topcu and Sengel [17] reported that unit weight decreased in hardened concrete with WCAs. While the unit weight of concrete containing 50% of WCAs was 2301 kg/m³, the unit weight of concrete with whole WCAs was 2251 kg/m³.

3.4. Apparent porosity and water absorption

Apparent porosity results for the PCIBs is presented in Fig. 12. As seen from Fig. 12, porosity of PCIBs with CSS, CW and MW increases with increment in fly ash replacement in the mixture. For CSS, porosity values are 10.3%, 10.7%, 11.5%, 15.8% and 18.5% for 0%, 10%, 20%, 30% and 40% fly ash replacement, respectively.

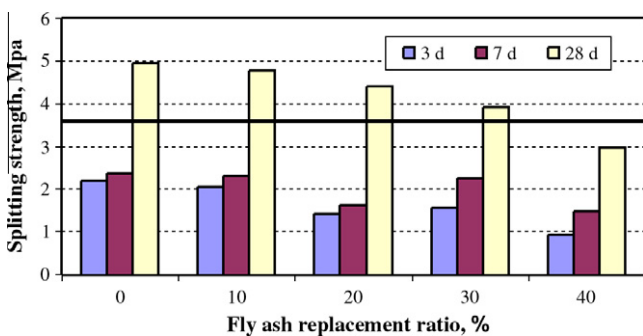


Fig. 6. Splitting strength of PCIB with CSS.

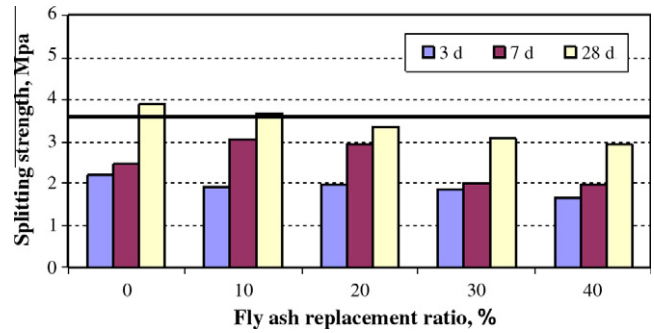


Fig. 7. Splitting strength of PCIB with CW.

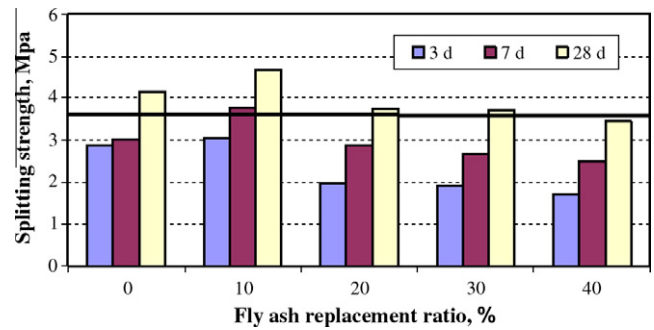


Fig. 8. Splitting strength of PCIB with MW.

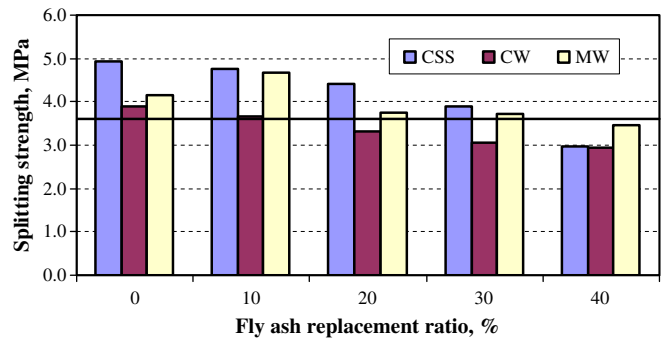


Fig. 9. Comparison of splitting strength of 28 days aged PCIBs.

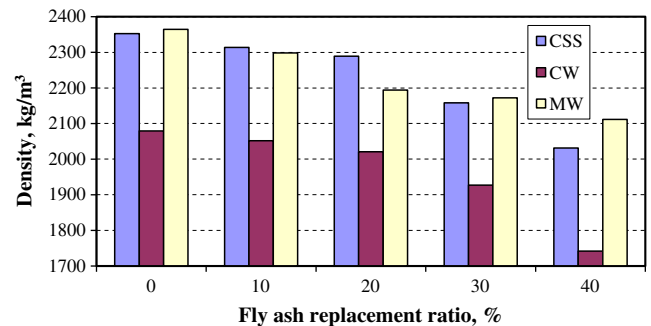


Fig. 10. Changing of density of PCIBs depending on fly ash content.

Porosity values of PCIBs with CW are 17.9%, 18.1%, 19.4%, 21.5% and 28.9% for 0%, 10%, 20%, 30% and 40% fly ash replacement, respectively. Porosity values of PCIBs with MW are 8.2%, 8.6%, 12.8%, 13.8% and 14.3% for 0%, 10%, 20%, 30% and 40% fly ash

replacement, respectively. MW increases less apparent porosity of PCIBs than those of CSS and CW.

Water absorption of concrete is naturally related to the nature of the pore system within the hardened concrete. Aggregate can also contain pores, but these are usually discontinuous. Moreover, aggregate particles are enveloped by the cement paste, which is the only continuous phase in concrete so that the pores in aggregate do not contribute to the water absorption of concrete. Thus, the influence of aggregate is quite small. The hardened cement paste has the greatest effect on the absorption of fully compacted concrete.

Water absorption of the blocks results are presented in Fig. 13. For CSS, water absorption values are 4.4%, 4.6%, 5%, 7.3% and 9.1% for 0%, 10%, 20%, 30% and 40% fly ash replacement, respectively. Water absorption values of PCIBs with CW are 8.7%, 8.7%, 9.6%, 11.1% and 16.6% for 0%, 10%, 20%, 30% and 40% fly ash replacement, respectively. Water absorption values of PCIBs with MW are 3.5%, 5.8%, 6.4% and 6.5% for 0%, 10%, 20%, 30% and 40% fly ash replacement, respectively. The highest water absorption values belong to specimens with CW. The lowest values belong to the specimens with MW.

There is a relationship between porosity and water absorption of concrete. In this respect, when Figs. 11 and 12 are considered together, this relationship can be seen clearly on the produced concrete specimens. A certain amount of mortar and cement paste from original concrete remains attached to stone particles in recycled aggregate. This attached mortar may be the main reason for higher porosity and water absorption values of PCIBs with CW. Topcu and Sengel [17] reported that in comparison with normal concrete, concrete including CW has a higher water absorption ratio.

Also, an increase in porosity and water absorption of PCIBs may be related to the densities of the produced CPIBs. While the densities of PCIBs decrease, the porosities and water absorption values of CPIBs increase as seen from Figs. 10–12.

3.5. Alkali silica reaction

Alkali–silica–reaction (ASR) is known as one of the most deleterious events that can occur in concrete: the reaction products are expansive and lead to crack formation. According to ASTM C 1260 [23], an aggregate is usually considered harmless if the expansion of cement–aggregate combinations is smaller than 0.1% at 14 days in NaOH solution at 80 °C. If the expansion ratio of cement–aggregate combination reached at the end of the 14 days is higher than 0.2%, this is considered harmful to aggregates. On the other hand, in the range between 0.1–0.2% and <0.1%, the expansion ratio means uncertain and harmless, respectively.

Consider the expansions of PCIBs with CSS, CW and MW. All our concrete specimens have sufficient resistance to ASR. As seen from Figs. 13–15, increment in FA in the mixture reduces the expansion

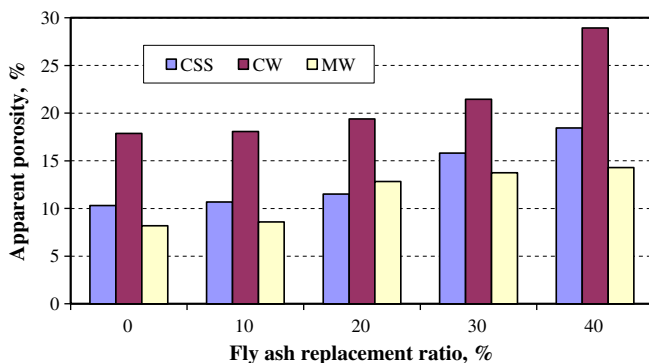


Fig. 11. Apparent porosity of PCIBs as a function of the fly ash content.

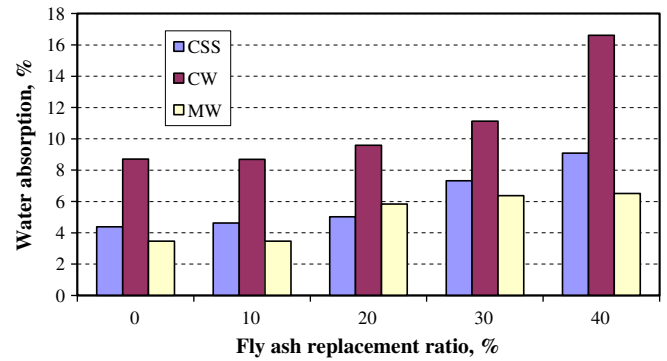


Fig. 12. Water absorption of PCIBs depending on fly ash content.

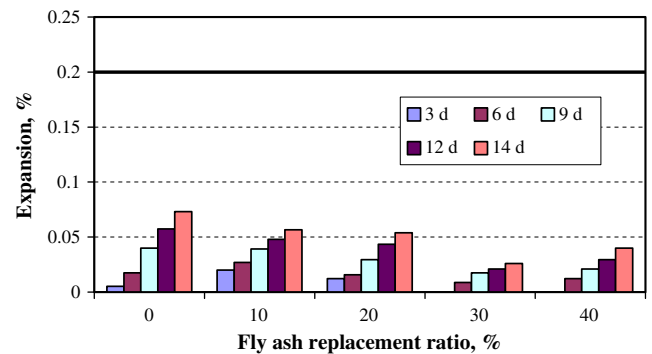


Fig. 13. Expansion of PCIBs with CSS.

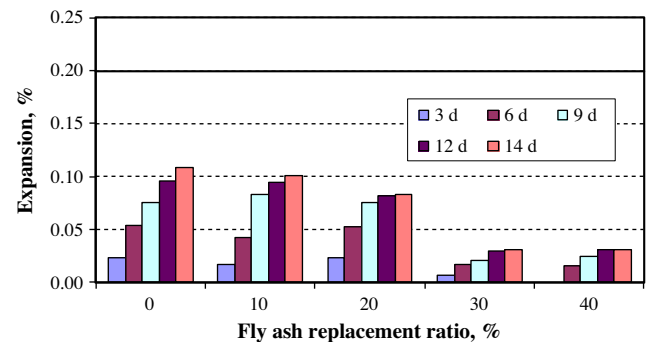


Fig. 14. Expansion of PCIBs with CW.

of concrete due to ASR. Also, it seems that MW has higher resistance to ASR effect than CW and CSS. This may be due to the low quantity of alkali silicate gel generated by reacting with MW.

3.6. Abrasion resistance

The abrasion resistance of concrete is strongly influenced by the compressive strength, surface finishing techniques, curing types, aggregate properties and testing conditions, i.e. dry or wet as reported before Gencil et al. [29]. The abrasion resistance reports of the different concrete types are shown in Fig. 16. While the other properties of PCIBs decreased with the use of CW fine aggregate, the abrasion resistance of PCIBs was increased. Evangelista and Brito [26] reported that the abrasion resistance seems to increase in ratio of 30% with the replacement of fine natural with fine recycled concrete aggregates. These assumed that this may be related

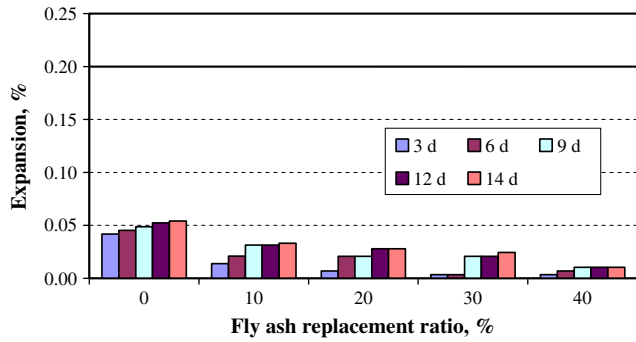


Fig. 15. Expansion of PCIBs with MW.

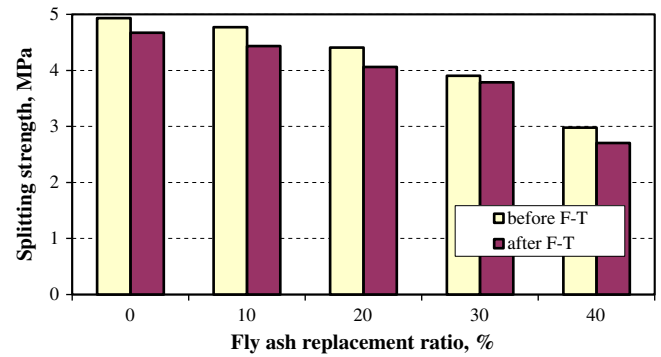


Fig. 17. Freeze-thaw resistance of PCIBs with CSS.

to a connection between the abrasion resistance and the bonding of the cement paste with to fine aggregates improved when recycled aggregates are used. Gencil et al. [29] explained this mechanism in detail in their work. Briefly as follows;

Abrasion increases with the applied load. As the abrasive particles achieve relative motion, shear forces are formed on the surface of the abraded material along with a normal load. While the load helps abrasive particles penetrate into the specimen surface, shear force helps the formation of grooves and scratches on the surface. Thus, material transfer from the specimen surface occurs by a combination of normal load and shear forces. In this respect, as well as coarse aggregates, well dispersed fine aggregates and their bonding with cement is very important.

3.7. Freeze-thaw (F-T) resistance

Micro-cracks mainly exist at cement paste-aggregate interfaces within concrete, even prior to any loading and environmental effects. When the number of freeze-thaw cycles (FTCs) increases, the degree of saturation in pore structures increases by sucking in water near the concrete surface during the thawing process at temperatures above 0 °C. Some of the pore structures are filled fully with water. Below the freezing point of those pores, the volume increase of ice causes tension in the surrounding concrete. If the tensile stress exceeds the tensile strength of concrete, micro-cracks occur. By continuing FTCs, more water can penetrate the existing cracks during thawing, causing higher expansion and more cracks during freezing. The load carrying area will decrease with the initiation and growth of every new crack. Necessarily the strength will decrease with FTCs [30,31]. Also, porosity and water absorption of paving blocks is an effective factor in point of freeze-thaw durability of blocks.

The results of freeze-thaw cycling (FTC) durability tests are presented in Figs. 17–19. As seen from these figures, splitting tensile strengths of specimens with CSS, CW and MW before subjecting to F-T cycle decreases with increasing fly ash contents. This

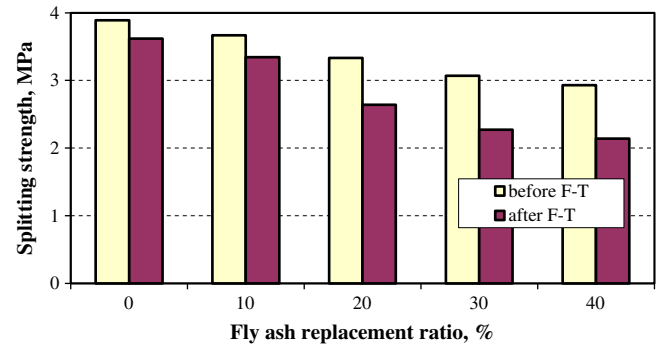


Fig. 18. Freeze-thaw resistance of PCIBs with CW.

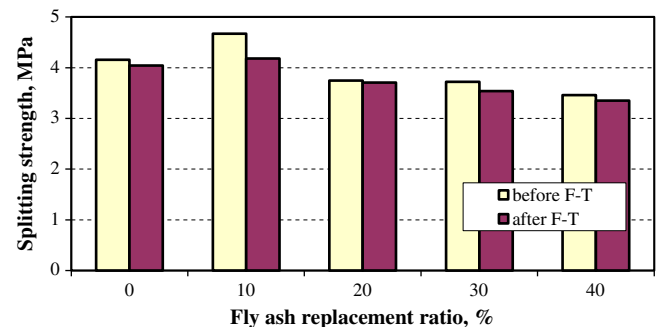


Fig. 19. Freeze-thaw resistance of PCIBs with MW.

situation remains after F-T cycles. However, when freeze-thaw resistance of PCIBs is evaluated separately, there is no significant effect of fly ash replacement up to 40% with cement in terms of F-T cycle durability. Strength losses of the produced concretes with CSS, CW and MW are negligible.

Gokce et al. [32] reported freeze-thaw cycles of concrete produced from recycled concrete aggregates with air content to be less durable. They also reported that freeze-thaw durability of concrete produced from fine materials of recycled concrete aggregates was higher than that of concrete produced from normal sand.

4. General discussion and a survey of results

The civil engineering construction industry is capable of absorbing large amount of waste – incorporating the waste into useful products. This is an example of a more general tendency of industrial ecology for a sustainable future of the world: industry by-products can be used as raw materials in other industries.

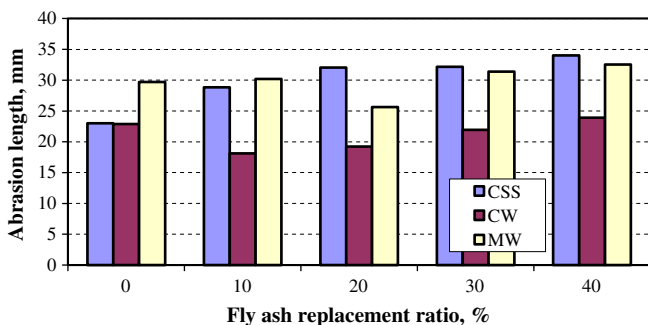


Fig. 16. Abrasion resistance of PCIBs depending on fly ash content.

Usage of waste materials in concrete presents several advantages: conserving mineral resources of a country such as aggregate and sand derived from nature, preventing environmental pollution, also a positive effect on a country's economy because of the high cost of waste storage. No natural resources constitute limitless reserves. For construction industry, maintainability and sustainable improvement aims primarily to protect environment by using alternative materials, new methods, and recycling.

The purpose of our work was determination of feasibility of using waste marble and concrete waste – which is an environmental problem – in fabrication of concrete paving blocks and the effects of waste marble on physical and mechanical properties of the blocks so produced. Several conclusions can be drawn from the present work.

- Compressive strength decreases as fly ash replacement ratio for each series is increased. Also replacement of CSS with CW and MW decrease compressive strength of paving blocks.
- Although paving blocks with CSS, CW and MW have around 2 MPa splitting tensile strength, all of them have satisfactory splitting tensile strength in 28 days. Paving blocks with CSS and MW fulfill the required strength (3.6 MPa) according to the standard except for 40% fly ash replacement ratio.
- The presence of marble aggregate causes a very small decrease of splitting tensile strength of the blocks.
- Density of paving blocks decreases by depending on increasing fly ash replacement ratio. While there is no significant change between paving block with CSS and MW, density of paving block with CW decreases significantly.
- Porosity and water absorption of paving block increase by depending on increment in replacement ratio of fly ash. At all fly ash replacement ratios, paving block with CW has the highest porosity and water absorption values.
- All paving blocks have high resistance to ASR effect.
- Fly ash increases resistance of the blocks to ASR.
- Contrary to other properties of paving block with CW, its abrasion resistance somehow is better than those of paving blocks with CSS and MW.
- Freeze–thaw durability of blocks decrease with increase of fly ash ratio in the mixture. After freeze–thaw cycle, paving blocks with CSS and MW at all fly ash replacement ratios except for 40% fulfill the required strength.
- Finally, we conclude that incorporation of waste marble and concrete provides concrete paving blocks of sufficient quality.

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