www.amlett.com, www.vbripress.com/aml, DOI: 10.5185/amlett.2014.amwc.1021 Published online by the VBRI press in 2014

Abrasion resistance of reactive powder concrete: the influence of water-to-cement ratio and steel micro-fibers

Çağlar Yalçınkaya[1*], Jędrzej Sznajder[2], Ahsanollah Beglarigale[1], Orkut Sancakoğlu[3], Halit Yazıcı[1]

[1] *Dokuz Eylül University, Department of Civil Engineering, İzmir, Turkey*
[2] *Gdansk University of Technology, Department of Civil Engineering, Gdansk, Poland*
[3] *Dokuz Eylül University, Department of Metallurgical and Materials Engineering, İzmir, Turkey*

[*] Corresponding author. Tel: (+90) 2323017042; Fax: (+90) 2324531192; E-mail: caglar.yalcinkaya@deu.edu.tr

Received: 13 October 2013, Revised: 28 November 2013 and Accepted: 14 December 2013

ABSTRACT

Reactive Powder Concrete (RPC) is characterized by high cementitious material content, very low water to cement ratio and steel micro-fiber reinforcement. This type of cementitious composite has greater ductility, durability and mechanical properties compared to traditional concrete. Abrasion resistance of the composite material is still not well understood, although it has a variety of applications, including bridge deck construction and floor covering. In the scope of this study, three water-to-cement ratios and various micro-fiber volume fractions were investigated. Mechanical properties under steam curing were determined. Cubic specimens with a 71 mm side were prepared for the surface abrasion test by means of Böhme apparatus. In addition, the flexural toughness and Charpy impact tests were performed on unnotched prismatic specimens. A relationship between loss of mass by the Böhme abrasion test and mechanical properties was investigated. Test results indicated that abrasion resistance and mechanical properties can be improved by incorporating steel micro-fiber. The positive effect of fibers can be enhanced by reducing W/C ratio. It seems that RPC has a great potential to use in civil engineering structures subjected to abrasion.

Keywords: Reactive powder concrete; abrasion; wear; toughness; steel fiber.

Çağlar Yalçınkaya is a research assistant in the Department of Civil Engineering at Dokuz Eylül University. Mr. Yalçınkaya is a Ph.D. candidate in the Civil Engineering Department (Contruction Materials Program). He received his M.Sc. (2009) in Construction Materials from Dokuz Eylül University, Turkey. The main research interests of Mr. Yalçınkaya are cement based composites and durability of construction materials.

Jędrzej Sznajder is a master thesis student at Gdańsk University of Technology. His discipline is Civil Engineering in a broad aspect.. He received B.Sc. degree in 2012 in Construction Modeling from Gdańsk University of technology. The main research interests of Mr. Sznajder are soil mechanics and durability of construction materials.

Halit Yazıcı is an associate professor at the Civil Engineering Department (Construction Materials Division), Dokuz Eylül University, Turkey. He has received his M.Sc. and Ph.D. degree in Civil Engineering from Dokuz Eylül University, Turkey. His active areas of research interest include the cement based composites. Dr. Yazıcı has published over 60 articles and conference proceedings in the field of construction materials science and technology.

Introduction

Depending on the fiber type and dosage, fibers can increase the toughness, energy absorption capacity, cracking resistance, and improve the impact resistance of cement based composites **[1–3]**. Fiber reinforced cement based composites have been used in civil engineering applications such as: shell domes, floors, rock slope stabilization, composite metal decks, aqueduct rehabilitations, seismic retrofitting, concrete pipes, repair and rehabilitation of structures, fire protection coatings, etc. **[4, 5]**.

Reactive Powder Concrete (RPC), also called Ultra-High Performance Concrete (UHPC), is a type of fiber reinforced cementitious composite. RPC was developed in the 1990s by Bouygues' laboratory in France. The first thorough study of this material was conducted in 1994 and 1995 by Richard and Cheyrezy **[6, 7]**. It is a special type of concrete which its micro grain, binder phase and steel micro-fibers are properly optimized. RPC can achieve compressive strength values between 150 – 800 MPa, while traditional concrete, which is used in current structures, usually has 20 – 50 MPa compressive strength. Its application in a wide variety of fields such as bridge engineering, structural elements, manhole covers, floor tiles, decorative panels for interior or exterior design has been increasing and developing.

Abrasion resistance of concrete is very important for civil engineering structures such as floors, pavements, concrete highways and hydraulic structures. However, abrasion behavior of RPC which has greater mechanical performance compared to traditional concrete is still not well understood although it has a variety of applications, including bridge deck construction and floor covering. The aim of this study is to clarify the performance of this material and to find correlations between some mechanical properties and abrasion resistance of RPC. For this purposes, three different water-cement ratios and fiber volume fractions were used as influence factors.

Experimental

Materials

Quartz supplied by Pomza Export Mining Company was used as aggregate with a maximum diameter of 1 mm. A new generation polycarboxylate-based superplasticizer (SP) manufactured by BASF was used. The physical, chemical and mechanical properties of the Portland cement manufactured by Denizli Çimento factory in Turkey (PC 42.5R) and properties of the silica fume (SF) supplied by BASF are presented in **Table 1**. A brass-coated steel-micro fiber (manufactured by Bekaert Corporation) with 0.16 mm diameter, 6 mm length, and 37.5 aspect ratio was used.

Preparation and production of mixtures

Twelve mixtures, with three water-to-cement (W/C) ratios (0.18, 0.22 and 0.26) which reinforced by 4 different amounts of steel fibers (0%, 1%, 2% and 3%), were produced. Mix designs are presented in **Table 2**.

The RPC mixtures were prepared in a Hobart mixer. A more complicated mixing procedure was applied compared to the conventional mixing procedure to obtain homogenous RPC mix. First of all binders, aggregates and steel fibers were mixed. After that, the mix water with half of the SP was added to the dry mix. After premixing, the remaining SP was added to the wet mixture. The final mixing was applied for 10 minutes at high-speed rotation (470 rpm). The mini-slump flow test, according to the EFNARC standards, was also conducted to verify the flow values of mixtures **[8]**. The initial diameter of the cone was 100 mm.

The mixtures were poured into prismatic moulds with dimensions of 40×40×160 mm for flexural and compressive strength tests and cubic moulds with dimensions of 71×71×71 mm for Böhme abrasion test. Fresh RPC exhibited self-compacting behavior. However, the moulds were vibrated for 20 seconds to reduce entrapped air content of sticky fresh RPC. Six hours after casting, the moulds were put in the steam curing cabin and heating period was started. The temperature of the cabin reached 100 °C within six hours and the specimens were kept in this temperature for twelve hours. A gradual cooling period was applied at the end of the curing period.

Flexural and compressive strength tests

Flexural and compressive strength tests were performed according to the ASTM C348 **[9]** and C349 **[10]** standards. Three-point bending test was applied to determine the flexural strength and load – deflection graphs by an electro-mechanic closed-loop testing system (loading rate: 0.02 mm/min for plain RPC and 0.2 mm/min for fiber reinforced RPC). The simply-supported specimens were loaded from their mid-span and the clear distance between the supports was 130 mm. The mid-span deflection was measured using an encoder to obtain load – deflection curves. Compressive strength test was applied on the two pieces left from flexural test. Three specimens for flexural strength and six specimens for compressive strength were tested for each mixture.

Abrasion test

Cubic specimens of 71±1.5mm were subjected to the abrasion test according to Turkish standard specifications TS 699-1987. Before the test, specimens were dried in an oven at 50 °C until reaching to constant weight. Böhme test apparatus used in this study is shown in **Fig. 1**. In compliance with TS 699 **[11]**, the abrasion system had a steel disc, which had a diameter of 750 mm and rotating speed of 30 ± 1 cycle/min, a counter and a lever, which could apply load of 300 ± 3N on the specimens. In the test procedure, 20 ± 0.5 g of abrasion dust (crystalline Al_2O_3) was spread on the disc, the specimens were then placed on it, the load was applied to the specimen and the disc was rotated for 4 periods. One period was equal to 22 cycles. After that, the surfaces of the disc and the specimen were cleaned. The above mentioned procedure was repeated 5 times (totally 5 × 88 = 440 cycles) by rotating the sample 90° in each period. The weight loss due to abrasion was measured.

Charpy impact test

Charpy impact test was performed according to the TS EN ISO 148-1:2010 **[12]** to assess its usability for RPC, and to find a relation between impact energy and mechanical properties, if possible. 71×71×10 mm slice were obtained by cutting from the cross-section of the cubic specimens parallel to the finishing surface. Then, slices of RPC were cut (10×10×55 mm). The tests were performed on unnotched prismatic specimens. Five specimens were tested for each mixture.

Table 1. Physical, chemical and mechanical properties of cement and chemical composition of cement and silica fume.

Chemical Composition (%)	Cement	Silica Fume	Properties of Cement	
SiO_2	19.90	92.25	Initial setting time (min)	170
Al_2O_3	5.91	0.88	Final setting time (min)	225
Fe_2O_3	2.10	1.98	Volume expansion (mm)	1.00
CaO	62.92	0.51	Specific surface(m^2/kg)	
MgO	1.25	0.96	Cement (Blaine)	371
Na_2O	0.38	0.45	SF (Nitrogen absorption)	20000
K_2O	0.90	0.12	Compressive Strength of Cement (MPa)	
SO_3	3.26	0.33	2 days	25
Cl^-	0.011	-	7 days	40
Loss on Ignition	3.94	-	28 days	50
Eq. Alkali	0.97	-	Potential composition (Bogue)	
			C_3S	56.97
			C_2S	12.60
			C_3A	12.02
			C_4AF	6.38

Table 2. Mix designs.

W/C ratio	0.18				0.22				0.26			
Fiber volume (%)	0	1	2	3	0	1	2	3	0	1	2	3
Water *	143	143	143	143	174	174	174	174	202	202	202	202
Cement *	785	785	785	785	785	785	785	785	785	785	785	785
Silica Fume *	196	196	196	196	196	196	196	196	196	196	196	196
0.5-1.0 mm Q *	693	678	662	646	684	668	652	636	665	649	634	617
0.0-0.4 mm Q *	462	452	441	430	455	445	434	424	443	432	422	411
SP *	60	60	60	60	35	35	35	35	18	18	18	18
Steel fibers *	-	71.7	143.4	215.1	-	71.7	143.4	215.1	-	71.7	143.4	215.1
Water/binder	0.15	0.15	0.15	0.15	0.18	0.18	0.18	0.18	0.21	0.21	0.21	0.21
Water/cement	0.18	0.18	0.18	0.18	0.22	0.22	0.22	0.22	0.26	0.26	0.26	0.26
SP (%)	6.76	6.76	6.76	6.76	3.91	3.91	3.91	3.91	2.04	2.04	2.04	2.04

*kg/m^3 Q = Quartz

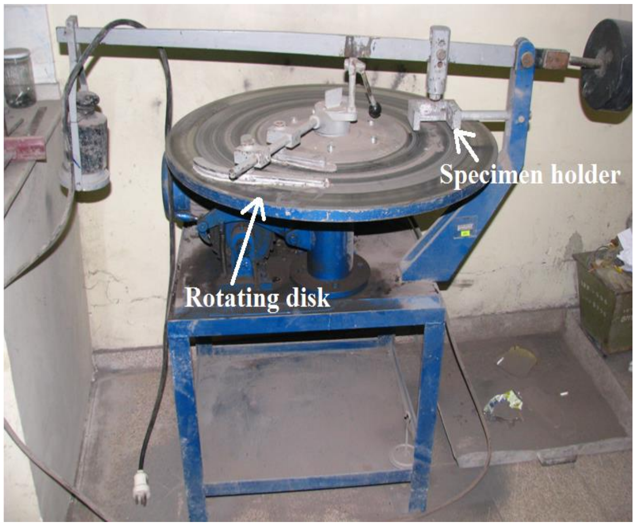

Fig. 1. Böhme apparatus used for abrasion test.

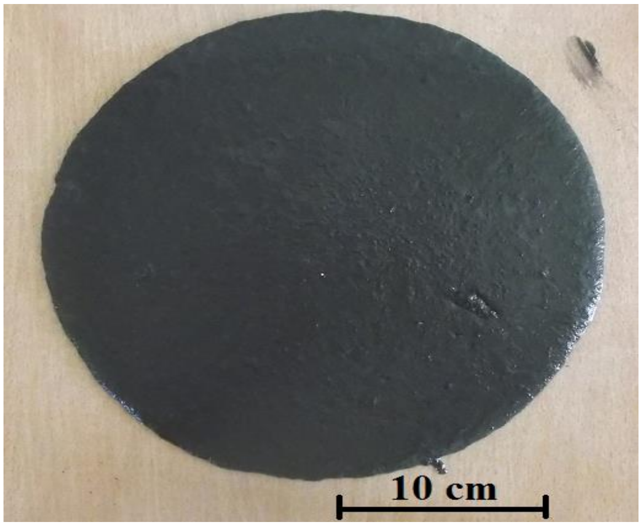

Fig. 2. The mini-slump flow testing of fresh RPC.

Results and discussion

Fresh state performance

Fresh RPC and slump-flow diameters depending on W/C ratio and fiber volume are presented in **Fig. 2** and **Fig. 3**, respectively. Preliminary tests demonstrated that in order to avoid segregation of micro steel-fibers, the upper limit of flow diameter was 280 mm and to achieve self-leveling behavior at fresh state the lower limit was 200 mm. Thus, flow diameter was aimed 260 mm for mixtures without fibers and different SP dosages were used for each W/C ratio. An increase in micro steel-fiber volume decreased flow diameters (**Fig. 3**). This behavior was more pronounced with decreasing W/C ratio. This can be attributed to additional inner friction due to fibers and higher viscosity of the mixtures with a low W/C ratio. Self-compactability can be maintained even if the fiber volume increases.

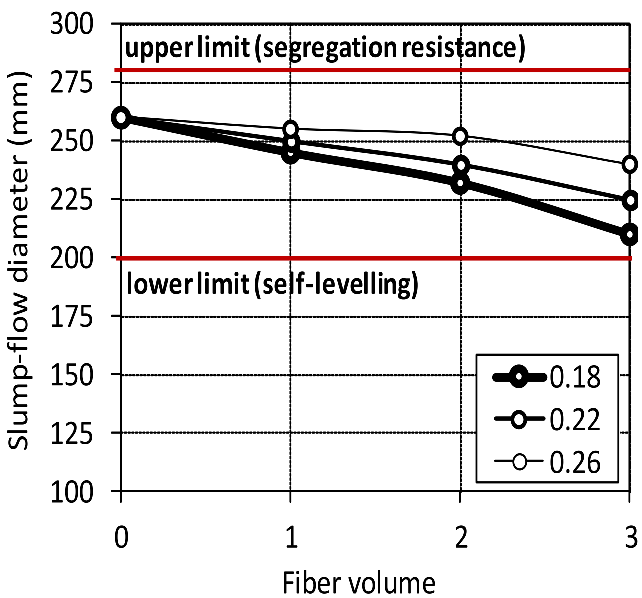

Fig. 3. Slump-flow diameter depending on W/C ratio and fiber volume.

Flexural performance

Load versus mid-span deflection curves of the mixtures with different fiber volumes and W/C ratios are presented in **Fig. 4**. Change in fiber volumes influenced the behavior of the mixtures dramatically. From the figures, it was found that for the unreinforced RPC, the material demonstrated relatively brittle behavior, the stress decreased rapidly with increase of mid-span deflection after peak load. Load carrying capacity and ultimate deflection values of a plain mortar (without fibers) have increased significantly by fibers inclusion. Mixtures with 2% and 3% fiber volume exhibited a deflection-hardening behavior that generates a higher load carrying capacity after the first cracking. However, first cracking point was not clear at 2% and 3% fiber volumes. Load increment was noted after first crack for 1% fiber volume. However, the second peak could not exceed the peak load. This behavior demonstrates deflection-softening. The high load carrying capacity after the peak load indicates an improved toughness. It is obvious that a decrease in W/C ratio enhanced fiber – matrix bond characteristics and improved flexural performance. This behavior was considerable for 2% and 3% fiber volume fractions. Higher peak load and descending tail of the curve caused greater toughness values compared to plain RPC without fibers (**Fig. 5**). The positive effect of fiber usage on flexural strength was more obvious at 2% and 3% fiber volume fractions, while 1% fiber volume did not improve the strengths (**Fig. 6**). In addition, the importance of W/C ratio was more noticeable at 2% and 3% fiber volume fractions. Flexural strengths increased by approximately 10 MPa owing to an increase in fiber volume from 2% to 3% for all W/C ratios. Maximum flexural strength values can be achieved with 3% fiber volume at all W/C ratios (25 – 32 MPa).

Compressive strength

The compressive strength of mixtures is presented in **Fig. 7**. All mixtures reached strength value higher than 150 MPa for 2% and 3% fiber volume and could be nominated as an ultra-high performance concrete. Compressive strengths of the mixtures without fiber were 121, 140, and 150 MPa at 0.26, 0.22, and 0.18 W/C ratios, respectively. Positive effect of fibers, in the case of 1% volume, on compressive strength was more pronounced in the mixture with 0.26 W/C ratio. The effect of W/C ratio on strength gain was more obvious at higher fiber dosages (>1%), particularly in 3%. This can be attributed to entrapped air due to workability loss at high fiber content **[13]**. The ultimate compressive strengths achieved by incorporation of 3% fiber volume were 190, 170 and 152 MPa for 0.18, 0.22, and 0.26 W/C ratio, respectively.

Abrasion resistance

The weight loss due to abrasion is given in Fig. 8. The abrasion loss of plain RPC for 0.26, 0.22 and 0.18 W/C ratios were found 2.4%, 2.3% and 1.84% (by wt.), respectively. The same values at 3% fiber volume were 1.76%, 1.76% and 1.52%, respectively. The addition of steel fiber in the composite produces a denser and stronger surface, which results in a higher resistance to abrasion. The RPC produced with a higher W/C ratio has a higher porousness and weaker C-S-H structure. Contrary to that, the low value of W/C ratio, especially in RPC with fibers, improves fiber – matrix interface and mechanical properties of cementitious matrix. The effect of W/C ratio on the abrasion resistance was much more significant at the fiber volume lower than 3%. It is obvious that particle loss under mechanical abrasion effect is much more difficult in the vicinity of steel fibers. Felekoğlu et al. **[14]** investigated abrasion resistance of self-compacting repair mortars (SCRM). Results indicated that addition of steel fibers (3%) decreased weight loss due to abrasion by 42%. The abrasion loss values of SCRM can be seen in Fig. 8 for comparison purposes. RPC demonstrated very low abrasion compared to SCRM. This result was more pronounced in the case of plain matrices. On the other hand, the weight loss difference between mixtures with various W/C ratios decreased with an increase in fiber volume fraction.

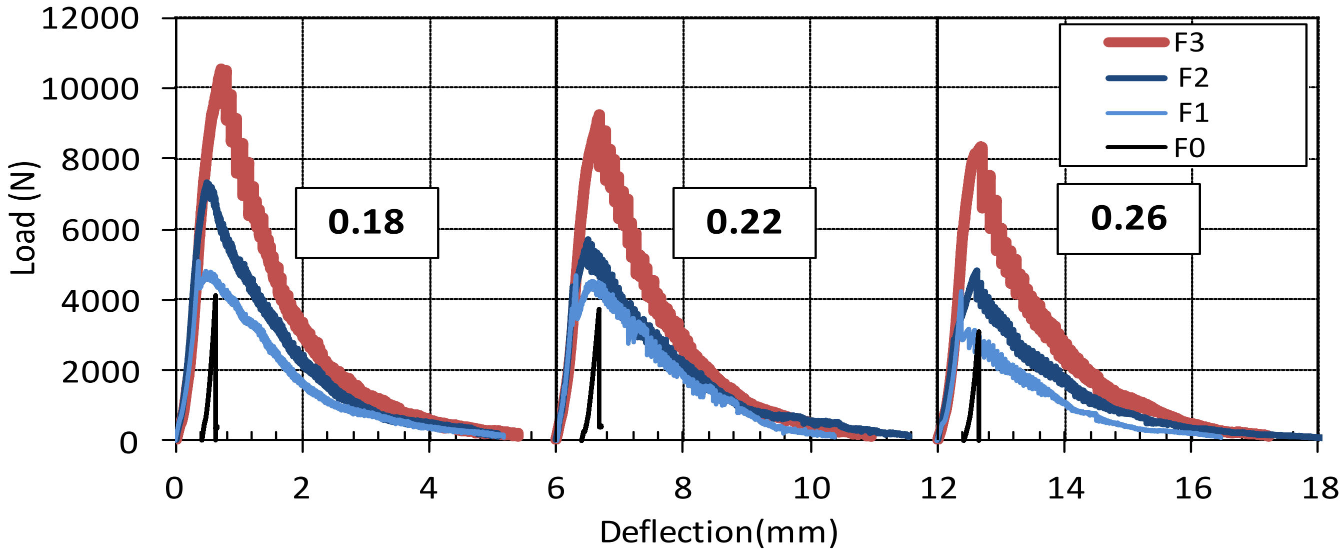

Fig. 4. Load vs. mid-span deflection curves of RPC specimens.

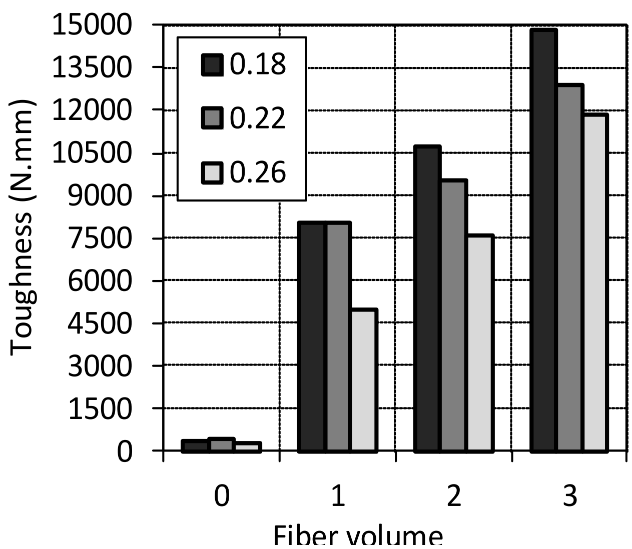

Fig. 5. Toughness of RPC specimens.

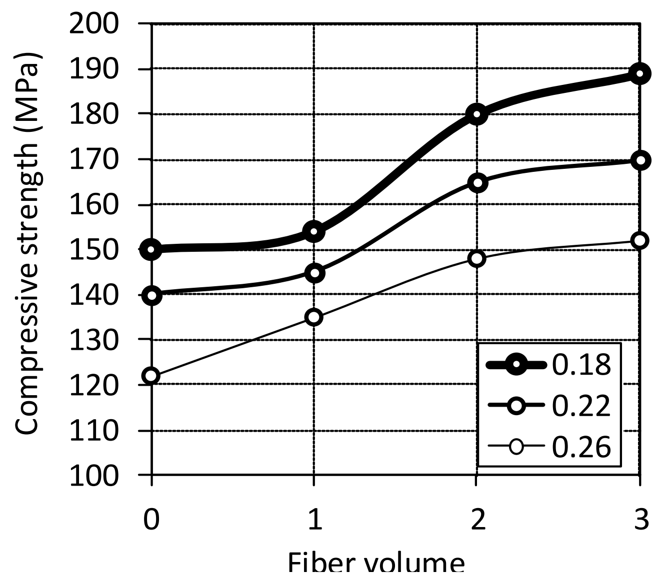

Fig. 7. Compressive strengths.

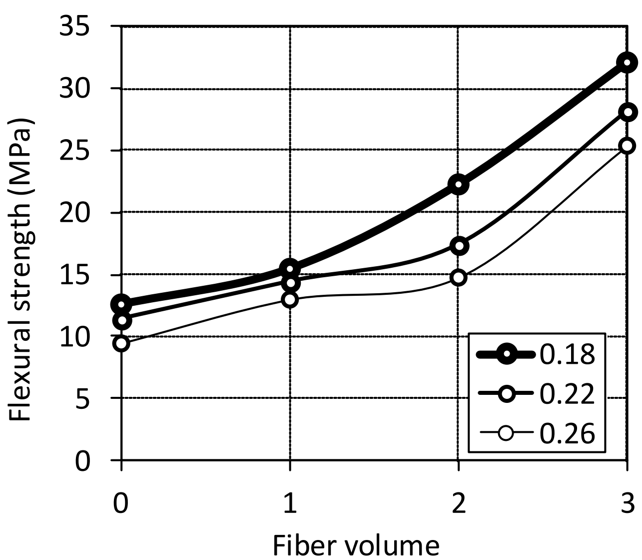

Fig. 6. Flexural strengths.

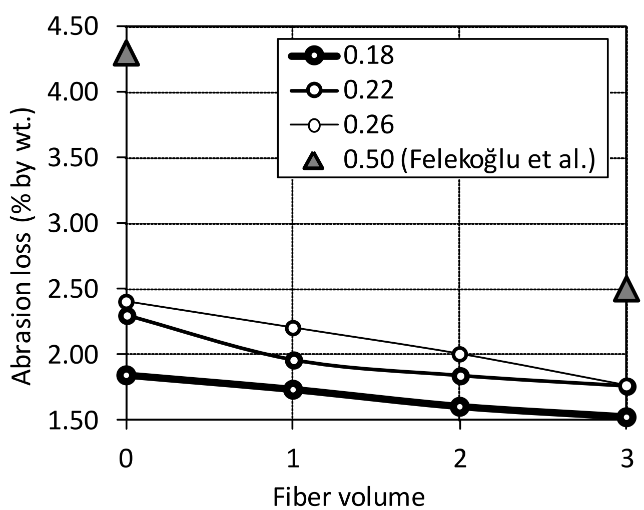

Fig. 8. Abrasion loss (% by wt.) depending on fiber volume and W/C ratio.

Fig. 9 shows the relationship between compressive strengths and mass losses. **Fig. 10** represents the relationship between toughness and mass loss. It should be noted that plain mixtures (non-fibred) with very low toughness were not taken into account in toughness vs. mass loss curve to achieve meaningful correlation. Mechanical properties were compared with abrasion loss values and a good correlation was obtained. The relations follow exponential functions. It is well known that compressive strength is the most important factor governing the abrasion resistance of concrete **[15, 16]**. Steel micro-fiber reinforcement improves not only flexural performance but also compressive strength in the case of ultra-high performance concrete. Furthermore, relationship between the toughness of fiber reinforced RPC and the mass loss is meaningful.

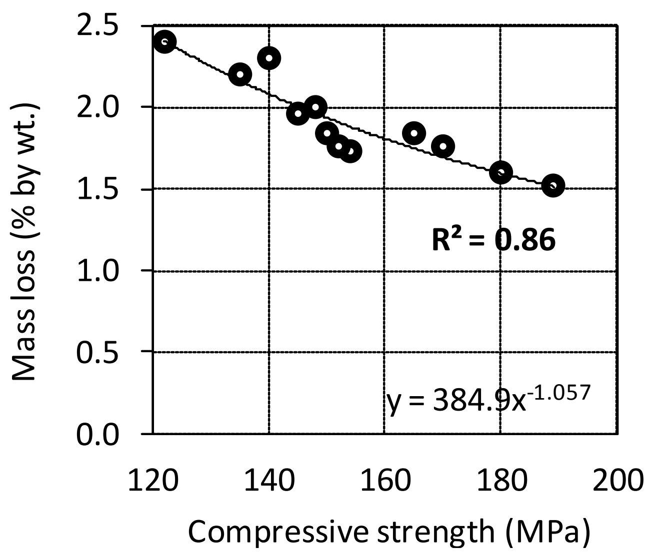

Fig. 9. Compressive strength vs mass loss**.**

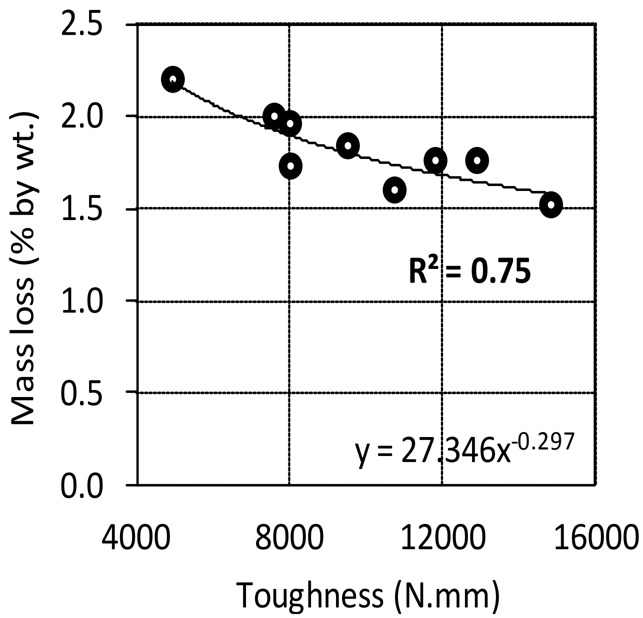

Fig. 10. Toughness vs mass loss.

Impact energy

According to the Charpy impact test results (**Fig. 11**) an increase in the impact energy is clearly seen with an increase in fiber volume ratio. This behavior is independent on W/C ratio. However, for the tested matrix, which has a brittle structure, this small impact energy values are improper to clarify the impact energy – mechanical behavior relation. Even if RPC as cement based composite has a greater mechanical properties compared to conventional concrete, a modified Charpy test setup and procedure are necessary to measure impact energy. In addition, micro cracks that occurred during specimen preparation (sawing, cutting) may have affected the results significantly. Some of studies devoted to a modified instrumented Charpy test can be found in literature **[17]**.

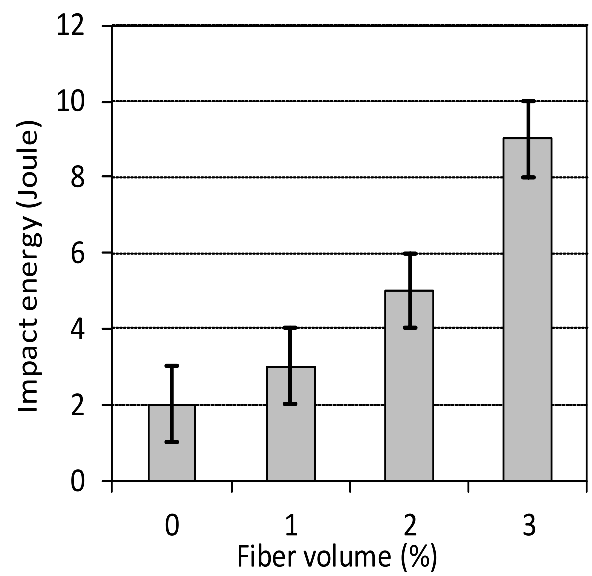

Fig. 11. Charpy impact test results.

Conclusion

It can be indicated from test results that RPC has a great potential to use in civil engineering structures subjected to abrasion. Abrasion resistance and mechanical properties can be improved by incorporating steel micro-fibers. The positive effect of fibers can be enhanced by reducing W/C ratio. Moreover, differences in abrasion resistance depending on W/C ratio can be eliminated using 3% fiber volume. Compressive strength and toughness values of RPC containing fibers were correlated with abrasion loss values and a good correlation was obtained. Prefabricated RPC elements especially for rain water drainage systems have been used increasingly in Turkey. It seems that RPC is a good alternative material under mechanical abrasion exposure due to heavy traffic loads.

Acknowledgements

This study was supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK, Project code: 110M691). The authors gratefully acknowledge the TÜBİTAK. In addition, the authors thank to Mr. Mehmet Yerlikaya from Bekaert-Turkey, Mr. Cevdet Kumaş and Mr. Okan Duyar from BASF-Turkey and Modern Beton for supplying materials.

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