ISSN 1392 - 1207. MECHANIKA. 2012 Volume 18(5): 498-502

Influence of fibres content on performance parameters of refractory concrete

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crossref http://dx.doi.org/10.5755/j01.mech.18.5.2697

1. Introduction

Refractory concrete is produced by the mixture of cement (binder), aggregates, additives and water. Due to resistance to high temperature, refractory concrete is subjected to severe situations, especially from a thermo mechanical point of view. High temperature affects strength reduction of the concrete due to destruction of the hydrated network of the cement and increase in porosity of the paste [1, 2]. Various kinds of fibres are used to improve the quality of refractory [3, 4]. Depending on the distribution and orientations of the fibres in matrix, addition of the fibres makes refractory concrete more homogeneous and isotropic and transforms it from a brittle to a quasiductile material [5, 6]. Reinforcement with fibres changes the behaviour of the matrix and this makes it possible to create the required strength reserve, retaining structural integrity even after development hairline cracks [3, 7, 8]. The results show, [9, 10] that adding ceramic fibre into concrete could increase the flexural strength of mortar obviously, but the effect of the flexural reinforcement was influenced by the fibre properties and kinds of the matrices.

Due to strong interest in utilization of waste catalyst produced by petrochemical industry, thermal non-equilibrium plasma spraying technology at atmospheric pressure was used for recycling this waste and production of microscale fibres with amorphous phase [11]. Diameter of as produced fibres was in the range from 0.2 µm by up to 20 µm. The length varied by up to 150 mm. After thermal treatment at high temperature crystallization of the material took place with the formation of thermal and chemical resistant mullite phase. No erosion or degradation of plasma sprayed fibres was observed after their interaction with complex binder [12]. It was also determined [13] that complex binder can be reinforced with up to 3% of the fibres without significant reduction of mechanical strength.

In this experimental study refractory concrete was reinforced with 1% and 3% of the fibres produced from recycled waste catalyst. The object is to investigate the contribution of fibres content on mechanical strength of refractory concrete after short and long exposure at 800ºC and 1000ºC temperature.

2. Testing procedures

By mixing complex or multicomponent binder (constituents are high alumina cement, metallurgical slag and liquid glass solution) with firestone (fine size up to 1 mm) aggregate refractory concrete was produced. Deflocculant FS-20 (BASF, Germany) and SiO_2 were used as additives. The chemical composition and properties of the binder components and micro silica used in this study had been listed in [14] and [15] respectively. Production and micro structural analysis of micro scale fibre was described in detail in [16]. Before the fibres were incorporated in concrete they were heat treated at 900ºC for 2 hours to get crystalline mullite phase. The fibres with 5 mm in length were used and added to concrete as the weight percentage of 1% and 3% of binder. 5% of micro silica was used in this study because silica increases density of complex binder and reduces linear shrinkage in temperature range from 800ºC up to 1000ºC [15]. Water-cement ratio was constant for all prepared mixes (Table 1).

Table 1

Composition of mixes (weight %)

Components	Mix codes		
	RC-0	RC-1	RC-3
High alumina cement	27.1	27.1	27.1
Metallurgical slag	7.8	7.8	7.8
Liquid glass	25	25	25
Firestone aggregate	34.85	34.85	34.85
Deflocculant FS-20	0.25	0.25	0.25
Micro silica*	5	5	5
Micro fibre*	-	1	3
water-cement ratio (w/c)	0.5	0.5	0.5

* above 100%

Samples of dimensions of 20×20×100 mm for flexural strength test were cast and cured in moulds for 3 days at above the water and 4 days at the ambient temperature of 20 ± 2ºC. After curing, all the samples were dried at 105 ± 2ºC until they reached constant weight. Each group of the samples was exposed to thermal treatment at 800ºC and 1000ºC for 3 and 48 hours and cooled to room temperature before testing. Ten samples were prepared for each test. Zwick Rowell universal machine with the capacity of 50 kN was used. Flexural strength (three-point) test was performed according to LST EN 993-6:2001. The applied load rate was 5 mm/min. Compressive strength test was carried out according to EN ISO 8895:2006 on the specimens, which had been broken after the flexural strength tests. The load rate was 10 mm/min. Bulk density and linear dimensional change (referred as shrinkage) after thermal treatment was determined according to the standards LST EN 993-1:2001 and LST EN 1094-6:2001, respectively. X-ray diffraction (XRD) patterns were obtained using Cu-Kα radiation (DRON-UM1) source to identify the existing phases by the commercial Search Match program.

3. Results

Measurements of the samples heat treated for 3 hours at 100ºC were not performed; therefore results of the fired refractory concrete were compared with the data of completely dry samples.

3.1. Apparent porosity and density

Changes in density and apparent porosity of refractory concrete with and without fibres as a function of applied temperature and thermal treatment duration are presented in Fig. 1 and Fig. 2 respectively.

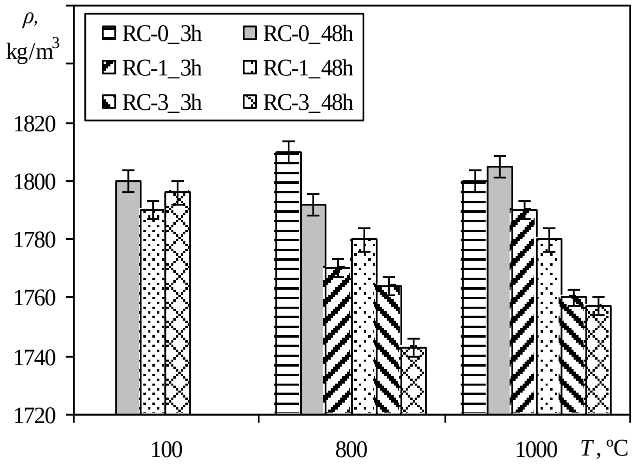

Fig. 1 The effect of fibres content on density of refractory concrete after treatment at various temperatures

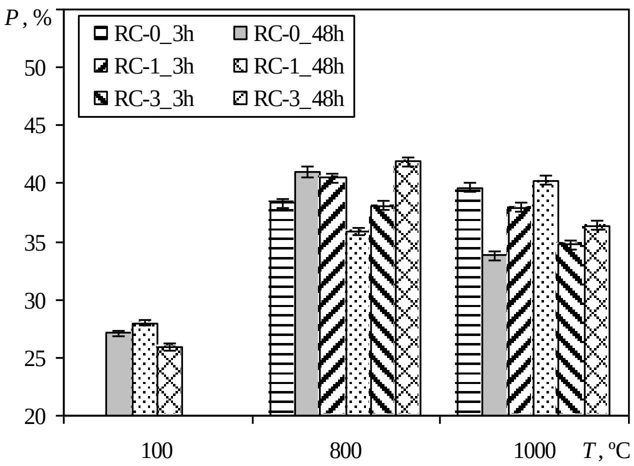

Fig. 2 The effect of fibres content on porosity of refractory concrete after 48 hours treatment at various temperatures

It was determined that the incorporation of the fibres reduced the concrete density in all temperatures investigated. The lowest density was measured for the samples with 3% of the fibres and this could be related to slow CA_2 (which is one of the major phases in the concrete (Fig. 3)) reaction with water at early stage of hydration [14, 16].

After short annealing at 1000ºC (Fig. 2) the formation of CAS_2 (anorthite) was identified (Fig. 3, f) and decrease of porosity with the increasing content of fibres was observed. Formation of the phases with low melting point, such as CAS_2 (anorthite) takes place due to incorporation of micro silica into refractory. Sintering of the liquid phase leads to reduction of porosity [15]. It was also observed that presence of the fibres in the composition determines porosity growth (by up to 10%) and density reduction (by up to 4%) with the increasing thermal treatment duration (Figs. 1 and 2).

3.2. Linear shrinkage

Fig. 4 shows the variations of linear shrinkage of refractory concrete. It was observed that shrinkage of the concrete with and without the fibres increases with the increasing temperature (Fig. 4). The results show that linear changes of all samples are greatly affected by the thermal treatment duration. The lowest value of the shrinkage (less than 0.6%) was measured for refractory with the highest content of the fibres after short annealing at both temperatures investigated (Fig. 4). Contrary, approximately two times lower shrinkage was determined for the samples with of 1% fibres (Fig. 4) after long exposure at high temperature. Meanwhile shrinkage of the plain concrete and the concrete with 3% of the fibres increased up to twice.

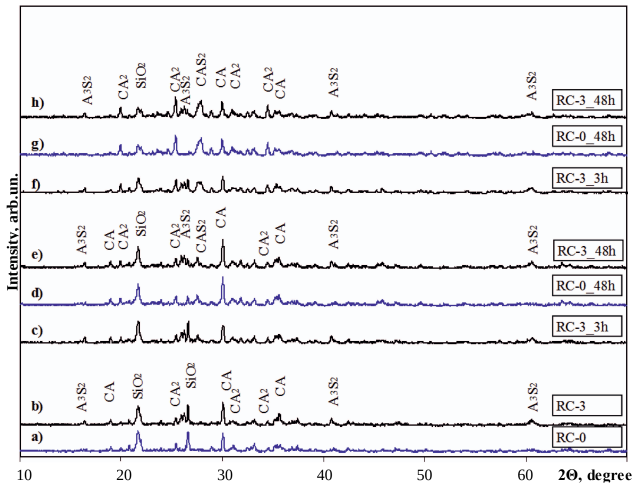

Fig. 3 X-ray diffraction patterns of refractory concrete with and without fibres after treatment at various temperatures: a, b - at 100ºC; c, d, e - at 800ºC; f, g, h - at 1000ºC

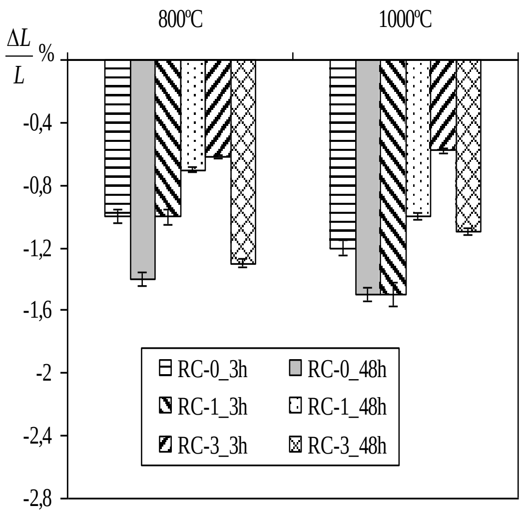

Fig. 4 The effect of fibres content on linear shrinkage of refractory concrete after treatment at high temperature

3.3. Compressive strength

The average measured compressive strength results (σ_C) of the refractory concrete with and without fibre are given in Table 2. The typical load-deformation curves of the plain concrete and with the fibres addition are shown in Fig. 5. The trend of curves of the refractory with 1% and 3% of the fibres was similar. During test the samples of plain refractory concrete typically exhibited very little cracking prior to failure. Failure occurred suddenly in a brittle manner and the curves show drop in the load after maximum peak was reached (Fig. 5). In contrast, the tested samples with the fibres exhibited a more ductile failure mode and cracks were formed progressively prior to failure. Continuous falls of the load or gradual softening behaviour has been observed in load-deflection curves for the concrete with the fibres (Fig. 5). Inspection of the curves indicated that peak of the load increases with the increasing temperature and heat treatment duration for all tested samples.

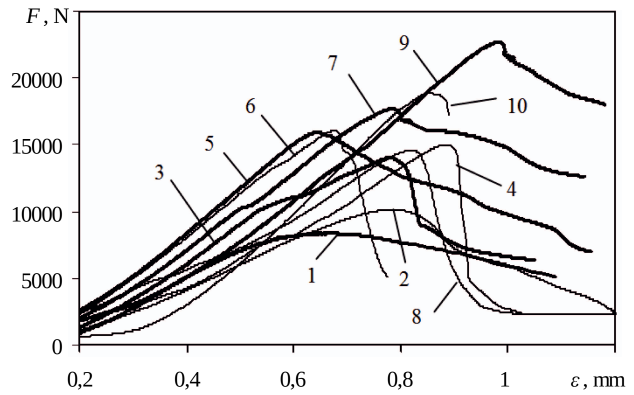

Fig. 5 Typical compression load-deformation curves of the plain concrete (*2*, *4*, *6*, *8*, *10*) and with fibres addition (*1*, *3*, *5*, *7*, *9*) heat treated at: *1*, *2* - 100ºC, *3*, *4* - 800ºC (3h), *5*, *6* - 800ºC (48h), *7*, *8* - 1000ºC (3h), *9*, *10* - 1000ºC (48h)

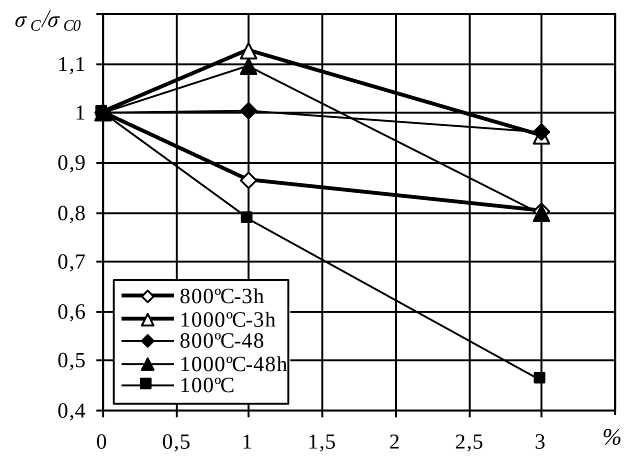

Fig. 6 The effect of fibre content on normalized compressive strength of refractory concrete after thermal treatment

Fig. 6 shows the effect of fibre content on normalized compressive strength. Normalized strength is expressed as the ratio of compressive strength of concrete with the fibres to the strength of the plain concrete at corresponding temperature. It was observed a trend of decreasing compressive strength with the increasing fibre content when temperature is lower than 1000ºC. Fibres content starts to be important after thermal treatment at 1000ºC, when the presence of 1% of the fibres gives by up to 10% higher compressive strength in comparison with the plain concrete (Fig. 6). Contrary, higher content of the fibres is not favourable.

Table 2

Summary of the results

Mix codes	Compressive strength σ_C, MPa	Elastic modulus E, GPa	Flexural strength σ_F, MPa	Flexural modulus E_F, GPa
100ºC-12 hours				
RC-0	28.3	1.30	11.7	2.70
RC-1	21.6	0.79	9.2	2.95
RC-3	12.7	0.76	8.2	3.35
800ºC-3 hours				
RC-0	48.6	1.67	14.7	3.98
RC-1	42.1	1.64	12.8	4.41
RC-3	38.9	1.46	12.1	3.73
800ºC-48 hours				
RC-0	46.7	1.61	14.0	2.95
RC-1	47.0	1.59	14.0	4.40
RC-3	45.1	1.41	12.4	3.26
1000ºC-3 hours				
RC-0	40.8	1.53	14.0	5.13
RC-1	45.8	1.49	14.2	5.59
RC-3	39.0	1.20	12.6	3.45
1000ºC-48 hours				
RC-0	52.5	1.45	12.6	3.09
RC-1	57.5	1.30	17.6	3.53
RC-3	42.0	1.18	14.4	3.41

Inspection of compressive strength results, summarised in Table 2, shows that presence of the fibres leads to increase of strength when temperature increases; meanwhile strength of the plain concrete reduces. However, thermal treatment duration had the strongest effect on the compressive strength of the samples. In comparison with the results obtained after short thermal treatment at 800ºC, long exposure at this temperature determined from 12% by up to 16% higher strength results for refractory with 1% and 3% of the fibres respectively. Contrary, compressive strength of the plain concrete reduced by up to 4% at the same conditions, but the value was the same order of magnitude as of the samples with the fibres (Table 2). Comparing results obtained after annealing at 1000ºC for 3 hours and 48 hours, it was observed that long thermal treatment enhanced compressive strength of the plain concrete by up to 29% as well as 26% and 8% of samples with 1% and 3% of fibres addition. However, the samples with 1% of the fibres showed the best results and were by up to 10% higher than the compressive strength of the plain concrete. Samples with 3% of the fibres had the lowest strength in all the temperature range investigated.

The results of elastic modulus of concrete with and without the fibres are given in Table 2. The data shows that addition of fibres into refractory concrete reduces modulus of elasticity and exhibit more ductile behaviour of the material. Moreover, the elastic modulus decreases with the increasing content of the fibres. Increasing temperature and heat treatment duration leads to the reduction of the modulus of elasticity of all tested samples.

3.4. Flexural strength

The typical flexural responses of plain concrete and with the fibres addition after exposure to high temperature for different duration are given in Fig. 7. Inspection of the curves indicates that presence of the fibres slightly decreased the peak flexural strength, but after long thermal treatment at 1000ºC the lower peak of the plain concrete was observed. Moreover, the increase of the peak with the increasing temperature was observed for the samples with the fibres addition instead of reduction observed for the plain concrete (Fig. 7). However, failure of all tested samples occurred due to the formation of a single crack within the centre of the prism, but presence of the fibres helped to bridge the crack, which led to a more ductile failure mode with higher residual strength (Fig. 7).

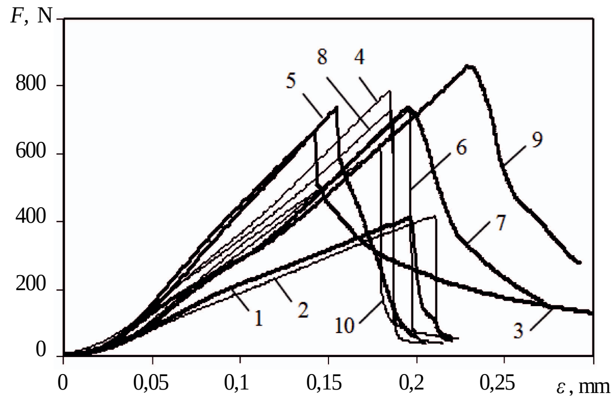

Fig. 7 Typical flexural load-deflection curves of the plain concrete (*2*, *4*, *6*, *8*, *10*) and with fibres addition (*1*, *3*, *5*, *7*, *9*) heat treated at: *1*, *2* - 100º°C, *3*, *4* - 800ºC (3h), *5*, *6* - 800ºC (48h), *7*, *8* - 1000ºC (3h), *9*, *10* - 1000ºC (48h)

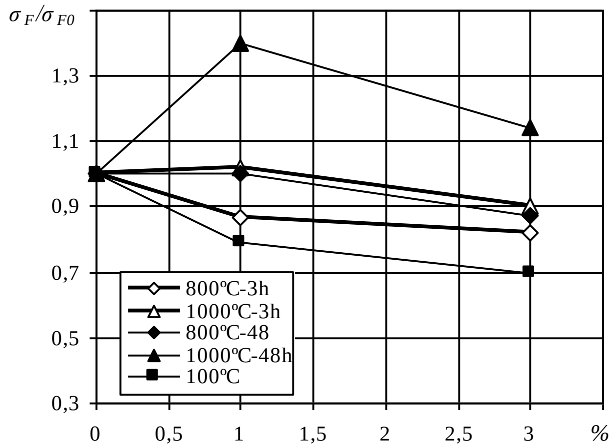

Fig. 8 The effect of fibres content on the normalized flexural strength of refractory concrete after thermal treatment

The effect of fibres content on normalized flexural strength of refractory concrete is presented in Fig. 8. The Fig. 8 shows that flexural strength reduces with the increasing content of the fibres when temperature is lower than 1000ºC, as well as in the case with the compressive strength. After thermal treatment at 1000ºC for 3 hours it was observed that flexural strength of the samples with 1% of the fibres was approximately the same as of the plain concrete, meanwhile, strength of the samples with 3% of the fibres was 10% lower. The positive effect of the fibres presence in composition was obtained after long exposure at 1000ºC temperature, when flexural strength of the refractory with 1% and 3% of fibres was 40% and 15% (for RC-1 and RC-3 respectively) higher than that of the plain concrete (Fig. 8). The results also show that flexural strength of the samples with the fibres increases with the increasing temperature and heat treatment duration, meanwhile the flexural strength of the plain concrete decreases (Table 2).

Flexural modulus of refractory concrete was also calculated and presented in Table 2. Inspection of the results indicates that lower content of the fibres increases tendency of the material to bend, meanwhile long thermal treatment reduces flexural modulus of all samples tested due to sintering processes in the material.

4. Conclusions

1. It was determined that compressive strength of refractory concrete with 1% of the fibres was by up to 10% and flexural strength was by up to 30% higher than that of the plain concrete after heat treatment at 1000ºC for 48 hours.

2. Modulus of elasticity of refractory concrete with the fibres is lower than of the plain concrete and reduces with the increasing content of fibres.

3. Addition of the fibre reduces thermal shrinkage of refractory concrete. The lowest thermal shrinkage results were determined for the concrete with 1% of fibres after long exposure at 1000ºC.

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PLAUŠO KIEKIO ĮTAKA UGNIAI ATSPARIŲ BETONŲ EKSPOATACINĖMS SAVYBĖMS

R e z i u m ė

Naudojant įvairios kilmės plaušus galima pagerinti tam tikras statybinių medžiagų savybes. Šiame darbe ištirtas ugniai atsparus betonas, papildomai modifikuotas plaušu, kuris pagamintas perdirbus naftos pramonėje susidarančias katalizatoriaus atliekas. Darbo tikslas – nustatyti plaušo kiekio įtaką betono mechaninėms savybėms po trumpalaikio ir ilgalaikio terminio apkrovimo. Ištirtos trys bandinių grupės – bandiniai be plaušo ir betono kompozicijos su 1% bei 3% plaušo. Nustatytas 3 ir 48 valandas 800ºC ir 1000ºC temperatūrose iškaitintų bandinių stipris gniuždant ir lenkiant. Gauti eksperimentiniai duomenys parodė, kad po ilgalaikio kaitinimo 1000ºC temperatūroje didžiausiu stipriu gniuždant ir lenkiant pasižymi betonas su 1% plaušo priedu. Tačiau didėjant plaušo kiekiui betono mechaninis stipris mažėja, nors plastiškumas išauga. Pastebėta, kad plaušo priedas mažina matmenų pokyčius po trumpalaikio ir ilgalaikio išlaikymo aukštoje temperatūroje.

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INFLUENCE OF FIBRE CONTENT ON PERFORMANCE PARAMETERS OF REFRACTORY CONCRETE

S u m m a r y

Various kinds of fibres are used to improve the quality of refractory. Properties of the refractory concrete with addition of the fibres produced from industrial waste catalyst were investigated. The object is to investigate the contribution of the fibres content on mechanical strength of the refractory concrete after short and long thermal treatment. Compressive and flexural strength of the plain concrete and modified with 1% and 3% of the fibres was determined after 3 and 48 hours firing periods at 800ºC and 1000ºC. Experimental results showed that the highest compressive and flexural strength was determined for the refractory concrete reinforced with 1% of the fibres after long exposure at 1000ºC. However, it was observed that the mechanical strength of the concrete decreases with the increasing content of the fibres; meanwhile, presence of the fibres exhibits more ductile behaviour. It was determined that addition of the fibre reduces thermal shrinkage of the refractory concrete after short and long thermal treatment at high temperature.

Keywords: fibres, mechanical strength, refractory concrete.

Received March 31, 2011
Accepted October 12, 2012