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Glass and Glass-Ceramic Binder Obtained from Waste Material for Binding Alundum Abrasive Grains into Grinding Wheels

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Abstract: The use of granular post-cupric slag (SiO_2–Al_2O_3–CaO–MgO-(FeO,-Fe_2O_3–K_2O–Na_2O)) as material for production of ceramic binders for abrasive tools was tested. Binder compositions of amorphous and crystalline structure (without any crystallisation catalyst) were composed on it basis. Using slag and conventional glass-making material as exclusive material for production, the binders enabling the bonding abrasive grains into grinding wheels with high physico-mechanical properties were obtained. © 1998 Elsevier Science Limited and Techna S.r.l.

1 INTRODUCTION

World-wide studies on proper collection and utilisation of material being by-products of other production technologies have been carried-out for tens of years. Dynamic industry development caused that amounts of waste materials is on the increase. Therefore it seems obvious that proper management of these material is necessary, the more because in some fields the depleting stocks of high-quality raw-materials, among other fluxing agents, nepheline syenite, feldspars have been observed.

Utilisation of waste materials leads to energy- and material-consumption in many manufacturing processes. There are many directions of utilisation of these materials, but now they are used mainly for production of building materials, from fly-ashes[1–4] and blast furnace slags[5] as well. A series of glass-ceramic materials[6,7] were developed on the basis of waste materials.

In Poland, the waste materials are the main subject of interests too, i.e. blast furnace slags and granular post-cupric slags tested mainly from the point of view their utilisation in production of building materials [8,9] and ceramic binders for abrasive tools.[10] The fast development of new abrasives and using higher grinding speeds have produced the new approach to the process to the types abrasive grains. These binders should have been modernised with regard to their quality at simultaneous reduction of material and energy consumption in the process of binder production. In the author's opinion one of the possibilities to satisfy these requirements is making use of a post-cupric slag as a principal cheap raw material for production of binders, both glass binders and glass-ceramic ones. Glass-ceramic materials produced on the basis of granular post-cupric slags, despite many valuable properties, have not been generally applicable yet, but probably it is only a matter of the nearest future.

2 EXPERIMENTAL PROCEDURE

2.1 *Materials and methods*

As a fundamental raw-material for composing the binders for binding the abrasive grains into abrasive tools, a granular post-cupric slag (a glassy form) being the by-product of a copper making process was used. This material is formed of complex oxide compounds of typical glass making components, such as Si, Al, Mg, Ca and others. Despite it is the glass, using this material as a binder directly is disqualified by a series of its properties, viz. comparatively high fusion temperature ($T_T = 1280°C$), forming a few crystalline phases during the heat treatment, which impair physico-mechanical properties of the material.[11] Although the material is characterised by high ability for crystallisation, but yet it could be used as ceramic binder if it is the glass-ceramic material with one type of a crystalline phase or it should have the amorphous structure. Moreover, in accordance with technological trends there is a tendency towards reduction of manufacturing costs of abrasive tools mainly by depression of a specific temperature of burning. Development of fusible binders is also of great importance regarding the super-hard abrasive grains in tools (diamond, borazone). It was assumed then that the fusion temperature of developed binders was about 1100°C, and applied unleaded frits contained oxides from the second group of the periodic system. In this connection the composition of such the binder should consist of the feldspar—$K_2O.A/_2O_3.6SiO_2$(31.8%), $CaCO_3$ (13.4%), $Al(OH)_3$(5.9%), SiO_2(25.4%), H_3BO_3 (23.7%). The refore, in order to approximate the initial composition of the material A (post-cupric slag) (Table 1), K_2O should be added to the assumed binder, which was partly changed for Li_2O (because it was a better fluxing agent). Furthermore, in order to obtain the glass-ceramic binder Al_2O_3, SiO_2, B_2O_3 should be added simultaneously to maintain the ratio CaO:MgO. The raw-materials were pulverised in a mortar 'Pulverisette 2' to obtain the graining of 0.12 mm. Prepared batches were fused in high-alumina ceramic crucibles in a silite furnace at the temperature of 1350°C. The batches are clarified by holding them at his temperature for 45 min. The frit was discharged to water and then it was broken up in two stages; in a porcelain ball mill and then in a mechanical agate mortar. The powders after pulverising were screened through a sieve of a lumen 0.063 mm. The binder composition and some of their properties are shown in Table 1.

Table 1. Chemical composition of fundamental material A and binders: A_1, glass-ceramic; A_2, glass

Binder mark	Composition (mol %)		
Oxide	A	A_1	A_2
SiO_2	41.5	57.1	53.16
Al_2O	13.5	4.3	9.65
CaO+MgO	33.0	19.4	8.28
Na_2O	0,5	2.3	2.21
K_2O	3.0	2.9	0.85
$FeO+Fe_2O_3$	8.0	3.4	2.13
MnO	0.3	0.1	0.07
CuO	0.5	0.1	0.05
ZnO	—	0.3	0.13
B_2O_3	—	7.6	17.27
Li_2O	—	—	2.49
BaO	—	—	3.60
Specific gravity ($g\,cm^{-3}$)	2,86	2,55	2,45
$\alpha \times 10^{-7}\,°C^{-1}$	84,0	78,8	58,5
Hv ($kG\,mm^{-2}$)	724	820	733
T_t (°C)	1280	1140	1100

Cylindrical shaped abrasive specimens dia. 15 mm and 10 mm in height were formed of prepared powdered binders and abrasive grains of noble alundum 99A 80 (150–180 μm); in groups of 10 with each binder (A_1 and A_2). Water solution of dextrin 10% by weight was used as lubricant. Designed characteristics of shaped abrasives are shown in Table 2.

Variables for heat treatment of abrasive specimens (temperature, time) were selected on the basis of tensile testing results. Abrasive specimens with the binder A_1 were fired at 1140°C in a silite furnace, then held at that temperature for 1 h and cooled at a rate of about 105°C h^{-1}.

Abrasive specimens with the binder A1 were fired at 1100°C, then held at that temperature for 1 h and free cooled down with a furnace. Mechanical tensile strength was determined by method described in Ref. 12. According to this method the cylindrical abrasive specimen (dia. 15 mm and 10 mm in thickness) was compressed towards the diameter between two flat bars made of sintered carbides.

Tensile stress is induced in the normal direction to the diameter. Testing was carried out using the testing machine Tensometer type W produced by Monsanto at speed of 1.6 mm min^{-1}. Young's modulus was tested on ring-shaped specimens 25×10×10 mm in dimension by means of the "Grindo-Sonic" tester. Obtained crystalline phases were identified by using X-ray diffraction analysis (XRD) at current intensity 19 μA and voltage 32 kV. A recorder tape was fed at 1°C min^{-1}. Testing of the selected element distribution in the binder fixing the alundum grains was carried out by X-ray microanalysis method using a microanalyser type JXA-3A made by Japan Electron Optics Laboratory. By means of an electron beam of about 3 μm in diameter incident perpendicularly to the microsection surface the specimen material was activated to the emission of characteristic X-rays in micro-zone of a diameter close to a diameter of the electron beam. Linear analyses were performed along the straight line through two adjacent alundum grains connected with a bridge.

3 RESULTS AND DISCUSSION

After suitable correction of the chemical composition of the fundamental material A as a result the glass-ceramic binder A_1 or the glass binder A_2 were obtained (Figs 1 and 2). The melilit phase $Ca_2(Al,Mg,Si)[Si_2O_7]$ was eliminated by introducing B_2O_3 and decreasing the amount of oxides type CaO and MgO in the batch A_1.[11] In consequence of the heat treatment of the binder A_1 at the temperature of the maximum nucleation, 820°C, nothing but the diopside $CaMg[Si_2O_6]$ was formed (Fig. 3). However, in order to obtain the proper distribution of the binder on the abrasive grains, the binder must be fused, i.e. heat treatment of the tools must be carried out at 1140°C. At this temperature, some of piroxene chains undergo decomposition, and some of them probably form micro-spheres, which are likely to have an influence on the crystallisation while slow cooling down. Formation of the crystalline diopside phase depends on a degree of supercooling, therefore at

Table 2. Characteristics of tested abrasive tools: V_z, volume fraction of grains in the grinding wheel; V_p, volume fraction of pores (%); V_s, volume fraction of the binder (%)

Constituent elements of the grinding wheel	E Modulus (kN mm^{-2})	34.5	43.5	52.5	61.5	70.5
	Structure number	Norton hardness symbol				
		I	K	M	O	Q
V_z		48.0	48.0	48.0	48.0	48.0
V_s	7	8.5	11.5	14.5	17.7	21.5
V_p		43.5	40.5	37.5	34.5	31.5

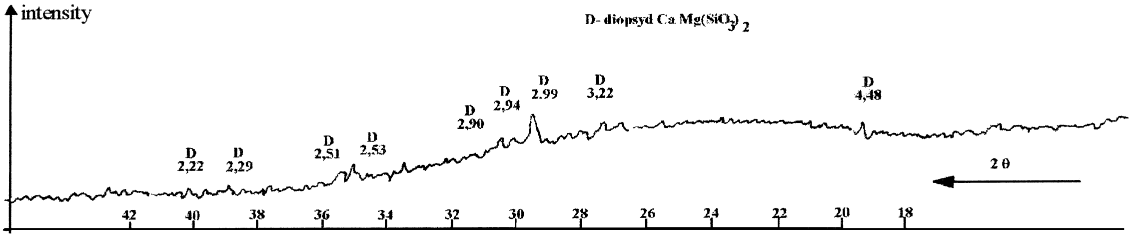

Fig. 1. Diffraction patterns of binder A1 fired at 1140°C/1 h and cooled at a rate 105°C/h.

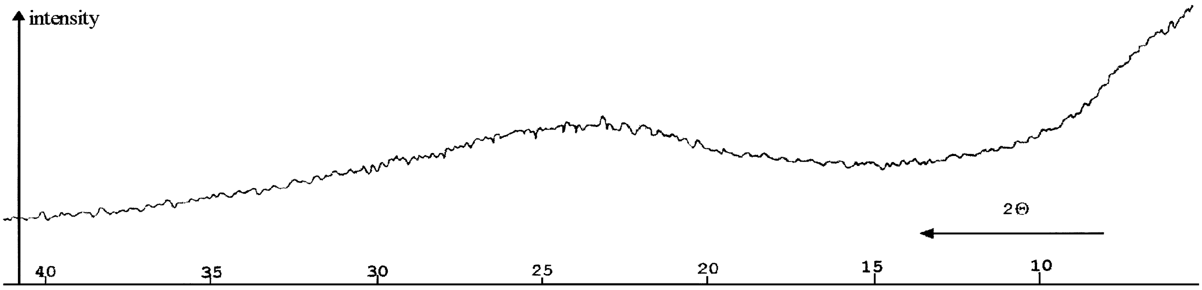

Fig. 2. Diffraction patterns of binder A2 fired at 1100°C/1 h and free cooled in a furnace.

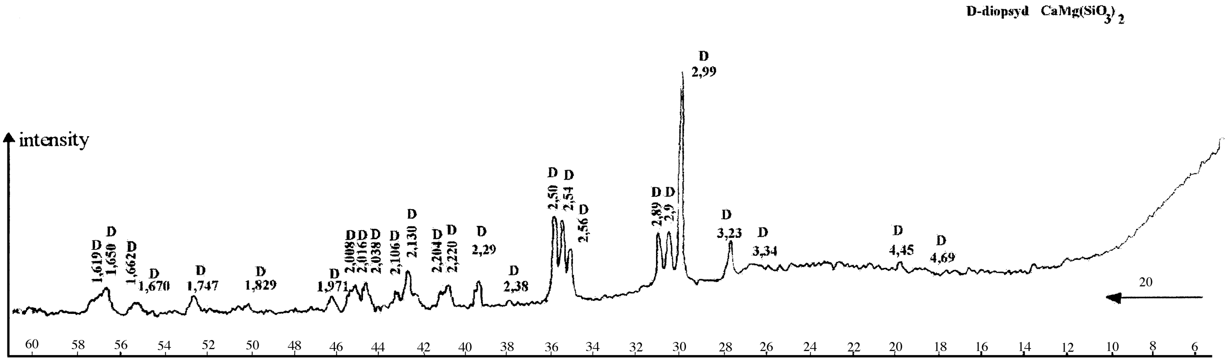

Fig. 3. Diffraction patterns of binder A1 fired at 820°C/2 h and rapid cooled at the critical temperature.

the cooling rate higher than 105°C h^{-1} the binder is amorphous (Fig. 4). Introduction of additional amounts of B_2O_3 compared with the binder A_1 very effectively decreases the crystallisation ability of the fundamental material. Additional decrease in the crystallisation ability is likely influenced by BaO, since as an ionic radius Me^{2+} increases at the same time the crystallisation ability of glass decreases. Depression of the fusion temperature in the binder A_2 is caused not only by the higher fraction of B_2O_3 but also by introduction Li_2O. Both the types of binders wet perfectly the abrasive grains and form regular bridges fixing the abrasive (Figs 5 and 6). Contact angle Θ is lesser than 30^0. Binder distribution on abrasive grains after firing is exemplified with the binder A1 (Fig. 7). Different structure of the binders A_1 and A_2 exerts an influence on the physico-mechanical properties of the abrasive samples. The binder structure have a distinct effect on the mechanical strength, specified by the tensile stress σ_r, (Fig. 8), whereas small differences in Young's modulus of the abrasive samples testify that the binder structure is not a parameter sufficiently sensitive on changes of Young's modulus of grinding wheels, (Fig. 9). It was observed for both the types of abrasive samples (with binders A_1 and A_2), that the dependence of the modulus E on the binder content in the grinding proceeded in similar way. Whereas the distinctly higher values of tensile stress (σ_r) have the abrasive samples with the glass binder (A_2), but only within the range to the characteristic M7 ($V_Z = 48\%$, $V_S = 14.5\%$, $V_P = 37.5\%$) (Fig. 8). The further increase in the binder fraction at the same volume fraction of the grain results in the distinct decrease in the tensile strength. At the same time for the specimens with the glass crystalline binder the σ_r value increases very slowly as the binder fraction rises, which can testify to other mechanism of the binder destruction. It is proper to mention that the tensile mechanical strength of the abrasive samples (of the specified characteristic) with conventional

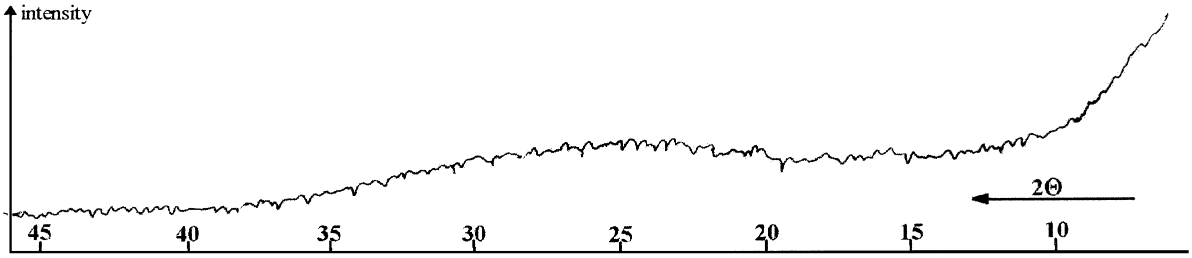

Fig. 4. Diffraction patterns of binder A1 fired at 1140°C/1 h and cooled down in a furnace.

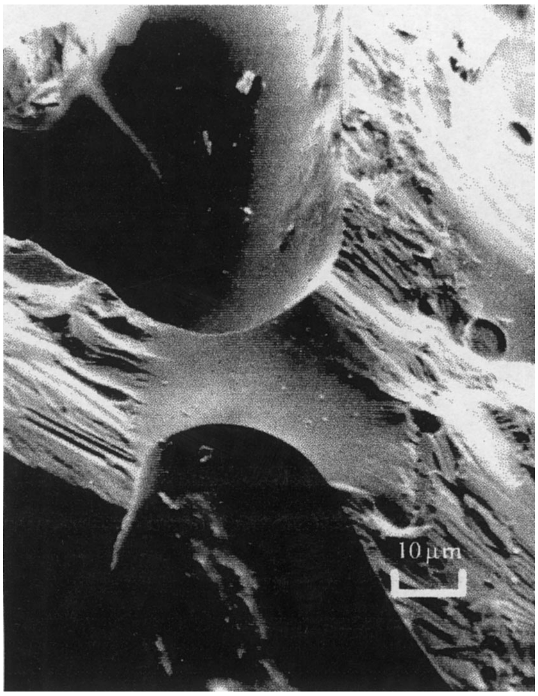

Fig. 5. Glass binder (A2) bridge fixing: abrasive grain, SEM 1000×.

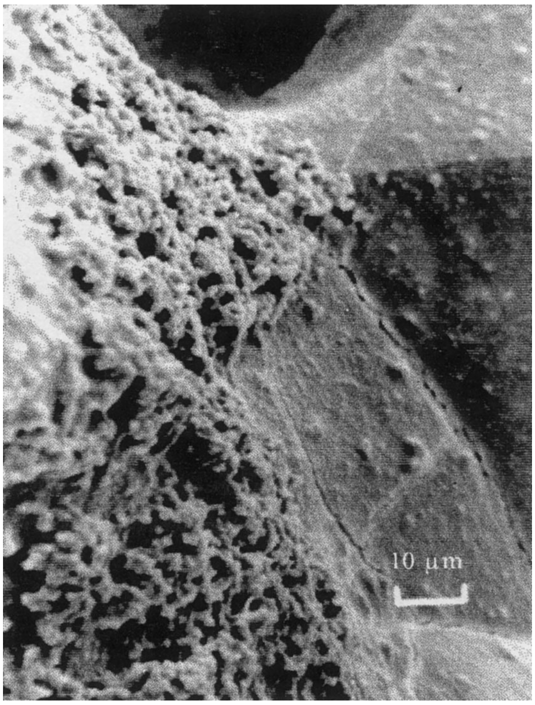

Fig. 6. Glass-ceramic binder (A1) bridge fixing: abrasive grain, SEM 1000×.

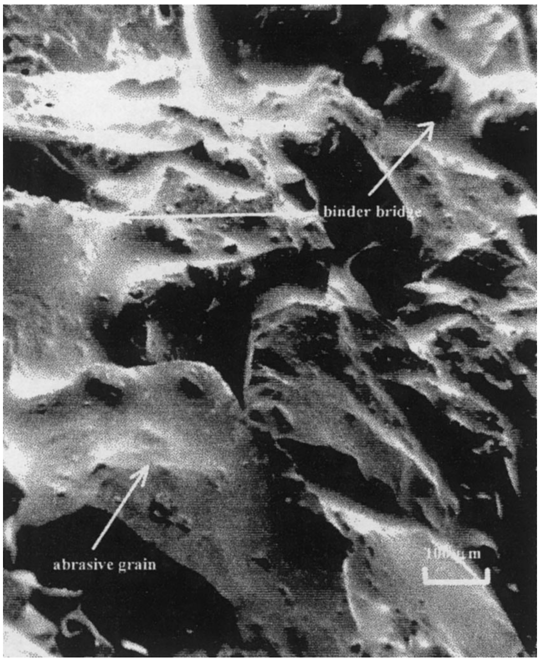

Fig. 7. Location of the binder (A1) in the grinding wheel 99A46M7 at the 1140°C, SEM 100×.

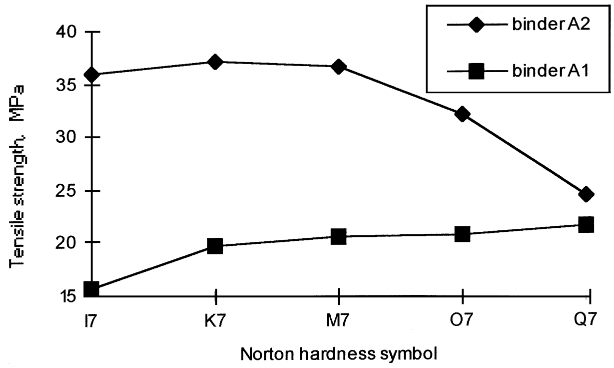

Fig. 8. Dependence of tensile strength of cylindrical abrasive specimens on Norton hardness symbol for structure no. 7; A1, glass-ceramic binder; A2, glass binder.

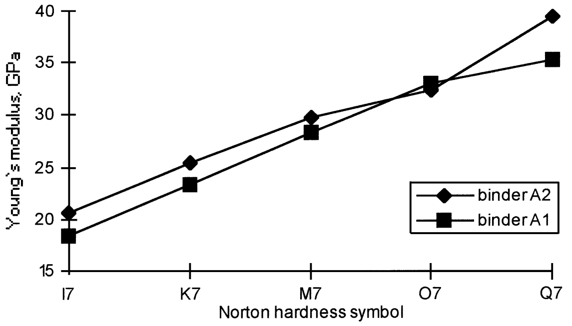

Fig. 9. Modulus E of abrasive specimens vs Norton hardness symbol for structure no. 7; A1, glass-ceramic binder; A2, glass binder.

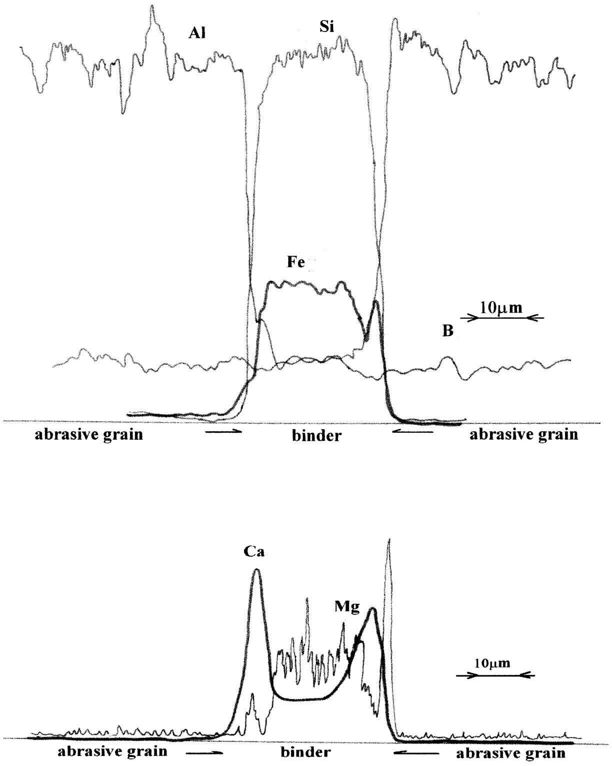

Fig. 10. Distribution of elements in bridge fixing abrasive grains in glass-ceramic binder A1.

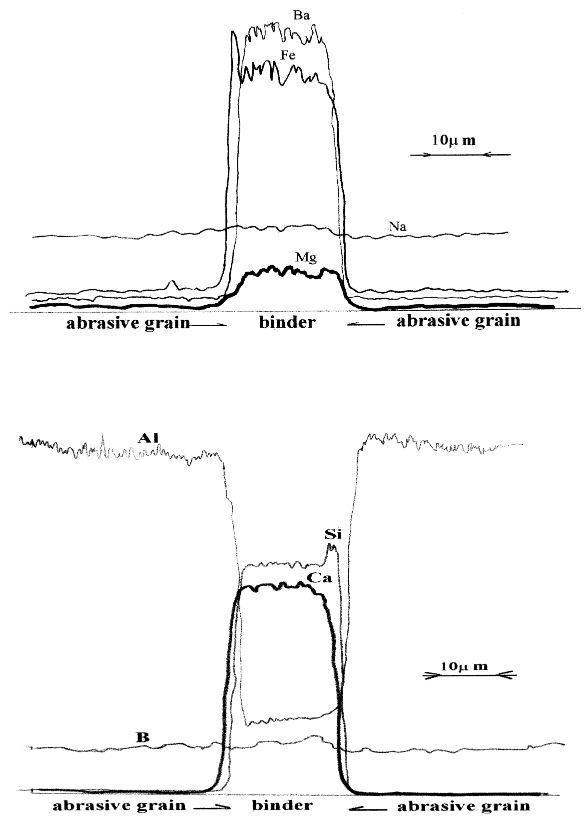

Fig. 11. Distribution of elements in bridge fixing abrasive grains in glass binder A2.

binders (with quartz, feldspar and clay fractions), with the grain 99A60 amounts to about 16 MPa, and the modulus E about 40 GPa.[12] Differences in the mechanical strength, i.e. behaviour of the abrasive specimens with the binders A_1 and A_2 under load are likely caused by various mechanisms of binder destruction, and also by phenomena proceeding on the grain–binder interface. There are presented distribution of selected elements in bonding bridges, i.e. Si, Al, Mg, Ba (Figs 10 and 11) for both the tested abrasive specimens. It follows from the drawings that in case of the binder A_1, the higher concentration of Mg and Ca on the grain–binder interface, Fig. 10 is observed and probably the higher mineralisation in the grain interface. Diffusion of Ca and Mg in the grain interface is not observed in the binder A_2, which additionally comprises ions Ba, which can decrease diffusive ionic mobility. Such uniform distribution of elements have a positive effect on the high strength of the abrasive specimens, but only up to 14.5% by volume of the binder in the grinding wheel. For higher hardness of tools (for which V_S increases) the binder structure take a more active role, which distinct effect could be visible during the effective operation of the grinding wheel, under conditions of heavy thermal–mechanical loads.

4 CONCLUSION

The developed compositions of the ceramic binders on the basis of granular post-cupric slag are fully qualified for fixing the alundum abrasive grains into the abrasive tool. Depending on ferric oxides and metals of alkaline earths the glass binder or glass-ceramic binder with the crystalline phase in form of diopside $CaMg[Si_2O_6]$ are obtained.

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