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Temperature-Induced Changes in Binders Produced from Concrete Waste: Strength and Rehydration Mechanisms

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ABSTRACT

This study aims to investigate the effect of elevated temperatures simulating fire exposure conditions on the strength and rehydration behavior of binders produced from concrete waste. The concrete waste was ground in a laboratory mill to a specific surface area of approximately 350 m^2/kg. The binder was burned at 400 and 600°C. Compression and density tests showed that the mechanical properties were not significantly affected at 600°C. The microstructure of the samples was analyzed, and the results indicated that the natural behavior of the samples during hydration and aging was identical to that of reference samples. Differential thermal analysis revealed that the mass loss curves during heating exhibit no abrupt transitions except at 133 and 778°C. Polymorphic changes in C_3S and C_2S begin at temperatures of 920°C and above. Therefore, it was concluded that burning temperatures of 400 and 600°C do not affect the mineral components of the binder. To evaluate the hydraulic hardening capacity and deformation behavior of the specimen, the results indicated that the behavior of the specimens was not affected by the firing of the binder at temperatures of 400 and 600°C. The results of this research revealed valuable insights into the effects of temperature, suggesting the potential use of concrete waste from building demolition exposed to high temperatures as a sustainable basic binder.

1. INTRODUCTION

The necessity of sustainable practices in the building sector, as the use of concrete waste in building is growing in popularity, especially as a binder ingredient. Concrete waste, especially the fine or dusty parts, provides an opportunity as additional cementitious material that might help cut waste and conserve natural resources. Presently, the manufacturing of concrete has placed a strong emphasis on using sustainable resources. This research paper aimed to study the thermal effects on the internal structure of recycled concrete and its impact on the resulting binder. In addition to being innovative, replacing conventional cement with alternative materials made from waste is a crucial step toward a more sustainable construction industry [1]. In construction and civil engineering, recycling these materials promotes the growth of a circular economy and greatly decreases landfill trash. Applying recycled concrete as base fillers for road building and other non-structural applications effectively shows the potential for sustainable reuse [2-4].

Esen and Kurt [5] conducted research on the effects of high temperatures on concrete's structural characteristics. Several minerals, such as barite, diatomite, silica fume, and F class fly ash, were substituted and added at volumetric rates of 10%, 20%, 30%, and 40% in addition to CEM I 42,5 R cement. Results proved that after being exposed to high temperatures (200, 400, 600, and 800°C), the samples were allowed to cool to room temperature before their compressive strength was determined. The results obtained showed that the highest water absorption rates were in Diatomite reinforced concrete, and the highest compressive strengths were obtained in Silica fume reinforced concrete [5]. Concrete reinforced with silica fume had the highest compressive strengths, but diatomite reinforced concrete had the highest rates of water absorption. Additionally, specific research has investigated the fiber-reinforced concrete's tensile strength following high-temperature treatment. Bezerra et al. [6] discovered that the flexural tensile strength of fiber-reinforced concrete was nearly the same as the value for the reference concrete specimen at room temperature after high-temperature treatment. Steel fibers significantly increase the heat and fire resistance of concrete-based composites, according to the study's test results.

Based on Maciá et al. [7], the compressive strength of materials containing 20% masonry waste reduced by 21% at 350°C, but the decline for materials comprising both recycled

and recycled concrete waste varied between 0% and 5%. At 500℃, the strength of the concrete that contained 30% masonry debris instead of natural aggregate decreased by 32%, while the strength loss of the other components under similar conditions was less than 9.5%. Under heat stress, concretes containing 20% mixed recycled aggregate performed the best. Understanding how concrete waste binders behave to high temperatures, which simulate fire exposure conditions, is necessary to assess how well they perform in heat-stressed environments. Multiple investigators have examined the behavior of materials, the variables that arise under high temperatures, and the thermal characteristics of concrete waste [8-10]. According to Lu et al. [11], the results showed that the CSH structure is weakened by rising temperatures. Portland cement is hydrated to form calcium hydroxide ($Ca(OH)_2$), another ingredient in concrete.

Three categories of recycled aggregates have been investigated by Garcia-Troncoso et al. [12]: Recycled concrete aggregate, recycled brick aggregate, and recycled concrete block aggregate. Due to the slight strength losses, 100% replacement of self-compacted concrete with recycled concrete block aggregate. Additionally, the results demonstrated that at high temperatures (400℃ and 600℃), recycled brick aggregate and concrete block aggregate performed higher than concrete containing natural aggregate. Since natural aggregate performs worse at room temperature, recycled brick aggregate is advised to partially replace it. However, it is more advised to utilize it in high-temperature settings [12].

Thermal conductivity, mass loss, specific heat, thermal expansion, and changes in macro and micro morphology before and after high temperatures were all examined by Xue et al. [13] in their study of the thermal properties of ultra-high-performance concrete with coarse aggregates exposed to temperatures ranging from 20℃ to approximately 900℃. According to experimental findings, ultra-high-performance concrete's thermal characteristics are significantly impacted by high temperatures. The thermal characteristics are also significantly impacted by coarse particles. However, the thermal characteristics are not significantly affected by steel fibers [13]. The impact of recycled aggregates on concrete exposed to high temperatures was examined by the authors [14, 15]. When heated to 600℃ and then cooled, the impact of recycled aggregates on the temperature distribution within a cylindrical specimen and the evolution of the thermophysical properties of concrete as a function of temperature were both explored. Analyses of thermal deformation at temperatures ranging from 20 to 800 degrees Celsius demonstrated the beneficial effects of using recycled sand in place of siliceous sand. The residual compressive strength and elastic modulus of all concretes drop as the temperature rises, whereas porosity increases.

Self-compacting concrete has been widely used in modern buildings in recent years [16, 17]. Therefore, it's expected that these buildings produce concrete waste. Fares et al. [18] studied the characteristics of high-temperature-treated self-compacting concrete (SCC). Each concrete mixture's The reduction in particle size of the added binder indicates its microscopic size, which can significantly influence its behavior and interactions within the concrete matrix by achieving a high specific surface area (SSA). This means that the powder particles are uniformly distributed, ranging in size from 1 to 50 μm. Figure 2 illustrates how the specific surface area of the powder increases with grinding time. This is attributed to increased friction between the particles, which in turn increases the crushing process, resulting in a more homogeneous distribution and accelerated chemical reactions.

specimens were heated to 150, 300, 450, and 600℃ at a rate of 1℃ per minute. The results showed a significant improvement in the mechanical properties of the samples at temperatures of 150-300℃ [18].

Abbas et al. [19] conducted an experimental investigation on twenty-one slab specimens made of self-compacting concrete. Three of the specimens (which represent control specimens) were retrofitted with CFRP sheets after loading until failure without burning, while the other eighteen slab specimens were retrofitted with CFRP sheets after burning and loading until failure. Every slab had undergone two-point stress and testing in a simply supported span. The primary factors were how the behavior of retrofitted one-way slabs was affected by varying concrete compressive strengths (20, 30, and 40 MPa), temperature levels (300, 500, and 700℃), and cooling rates (both progressive and abrupt). Slabs retrofitted with carbon-fiber reinforced polymer (CFRP) sheets showed greater deflection than the control slabs at ultimate loads, and the experimental results generally show that the recovered flexural strength values were almost equal to or lower than those of the reference slabs. After loading, the retrofitted control slabs recovered between 93.95% and 97.92% of their pre-refit load capacity, whereas the other slabs recovered between 42.0% and 84% of the original control specimens' load capacity. The majority of the tested slabs collapsed due to mid-span concrete crushing, and in a small number of cases, partial debonding of specific retrofitting systems was also noted [19].

From the above, research has shown the effects of different temperatures on the mechanical properties of different types of concrete, but studies have not been sufficient on the effect of high temperatures on the binding material resulting from concrete waste exposed to burning. The novelty lies in studying the properties of the binding material resulting from concrete waste exposed to burning as a simulation of the conditions that the structure may be exposed to during demolition or fire.

2. EXPERIMENTAL PROGRAM

2.1 Binder preparation and evaluation

In this study, recovered concrete waste from building demolition was collected and crushed using a laboratory jaw crusher, then sorted into smaller sizes to facilitate grinding and achieve the required surface area. To grind the concrete waste chips, a VM-20 vibrating mill was used. Similar to ball mills, the mill uses a rotating shaft to shake the working chamber, igniting the grinding material inside. The mill is powered by an electric motor operating at 2,200 rpm and producing an output force of 2.2 kg_f/min. Steel balls comprise 80% of the working chamber volume. Motion is transmitted to the balls within the chamber as the shaft rotates. The binder was obtained by screening concrete waste products, with sizes ranging from 0 to 0.315 mm, and containing the highest percentage of non-hydrated C_3S and C_2S. Finally, the binder was obtained by grinding the screening products from the vibrating mill to a specific surface area of 350 m^2/kg, which is close to the surface area of ordinary Portland cement [20]. Figure 1 represents the stages of binder preparation. The chemical, mineral, mechanical, and physical properties of the

binder are listed in Tables 1 and 2.

Figure 1. Procedures of binder preparation

Table 1. The chemical and mineral composition of binder obtained from the screening of concrete waste

Chemical Composition (% wt.)	**SiO_2**	**CaO**	**MgO**
	37	39	3
Mineralogical Composition (% wt.)	C-S-H	$Ca(OH)_2$	$CaCO_3$
	High	Medium	Medium to high
Chemical Composition (% wt.)	Al_2O_3	Fe_2O_3	SO_3
	13	5	2
Mineralogical Composition (% wt.)	C_3S	C_2S	C_3A
	Low	Low	Low

Table 2. Mechanical and physical characteristics of binder obtained from the screening of concrete waste

Setting Time (hr: min)		**Flex. Strength (MPa)**		**Comp. Strength (MPa)**	
Start	End	3 days	28 days	3 days	28 days
0:27	1:15	1.7	3	4	9

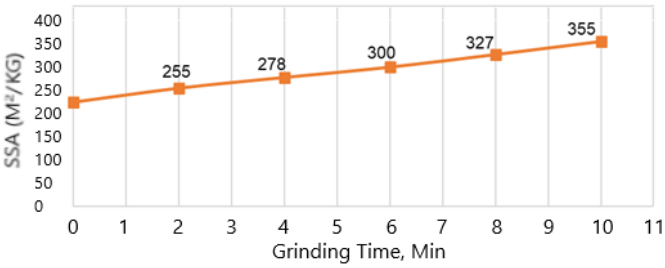

Figure 2. Change in SSA of binder from the screening products of concrete waste vs. grinding time

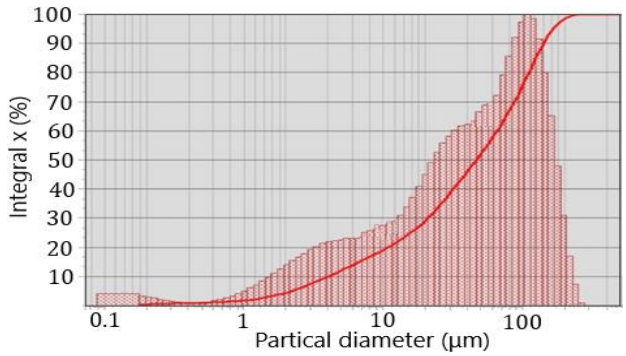

Figure 3. Granulometric composition of binder from the screening products of concrete waste (SSA = 350 m^2/kg)

According to the content of different fractions and their respective ratios, the particle size distribution curves show a shift to the left, indicating a reduction in the size of the fractions, which is correlated with an increase in the SSA, as illustrated in Figure 3.

Table 3 displays the results of the granular analysis of the binder under study, providing a good indication of the grain distribution in the binder. It is observed that with increasing the specific surface area (SSA) of the binder particles, the content of fractions with diameters ranging from 10 to 50 µm decreases from 35% to 30%, while the fractions in the 5-10µm range remain unchanged. Furthermore, as the SSA of the binder particles increases, the content of particles down to 100 nm in the resulting powder also increases. This indicates that a higher binder content is accompanied by a higher proportion of fine particles in the powder. Specifically, for binders with SSAs of 250, 300, and 350 m^2/kg, the content of particles down to 1000 nm is 3%, 5%, and 5%, respectively.

Table 3. Fractional composition of binder from the screening products of concrete waste

Fractional Composition (µm)	**Binder from the Screening Products of Concrete Waste (%)**		
	SSAs (m^2/kg)		
	250	**300**	**350**
0–0.1	0.05	0.05	0.05
0.1–0.5	1	2	2
0.5–1	1	2	2
1–5	5	7	7
5–10	5	5	5
10–50	35	30	30
50–100	53	53	53
Content of fractions 10–1000 nm (%)	Less than 3	4-5	4-5

To simulate the burning of concrete waste from demolished buildings and structures, the binder powder was heated to temperatures of 400°C and 600°C and cured for two hours in a laboratory furnace. The mechanical, chemical, physical, and thermal properties were studied after combustion. These post-combustion properties were compared and evaluated against samples of the uncombusted binder using modern laboratory equipment, as described in the next paragraph.

2.2 Characterization of devices

In this study, Analysette 22 NANOTEC PLUS was used to analyze the particle size and granular composition using laser diffraction technique to measure the particle size distribution in the sample. A laboratory furnace heated to 1000°C was used to study the binder properties and thermal behavior. Tescan MIRA 3 LMU scanning electron microscope (SEM) with an accelerating voltage of 8.0 kV was used to analyze the morphology of the materials and small concrete samples, measuring 15 × 15 × 4 mm. This microscope can be operated in various vacuum levels up to 150 Pa. An "ARL X'TRA" XRD model was used to perform chemical and mineralogical analysis of samples derived from demolition waste. Using a Thermo Fisher Scientific, the phase composition of the materials, their surface quality, and their structural properties, as well as crystallographic, quantitative, and qualitative factors, could be determined. Differential Thermal Analysis NETZSCH STA 449F1 to determine the thermal behavior of raw materials during heating or cooling as a result of chemical

and physical changes. A PSKH-10A device was used to monitor the technological processes of dispersing solid materials, subsequently measuring the specific surface area and average particle size of the materials, in addition to measuring the gas permeability coefficient of open-porous samples. TONI CALTRIO device was also used to determine the amount of heat released during the hydration process to demonstrate the effectiveness of the binder. Using a scanning electron microscope (SEM), the microstructure of the concrete samples was carefully examined.

3. RESULTS AND DISCUSSION

3.1 Differential Thermal Analysis (DTA)

Figure 4 shows the DTA pattern of the hydrated binder obtained from concrete waste screening. It shows an endothermic effect with a maximum temperature of 133.3°C, which is explained by the intensive removal of adsorbed water at 120-150°C, and there is combustion of organic materials at around 300°C [20], then the stage of endothermic reactions begins. The dihydroxylation of portlandite is linked to the endothermic action, which reaches its maximum at 500°C. The liquid phase of concrete is saturated with calcium hydroxide because the active mineral ingredient, in this case, concrete waste, did not absorb and bind all of the hydroxide, as evidenced by the existence of such a strong endo effect of portlandite.

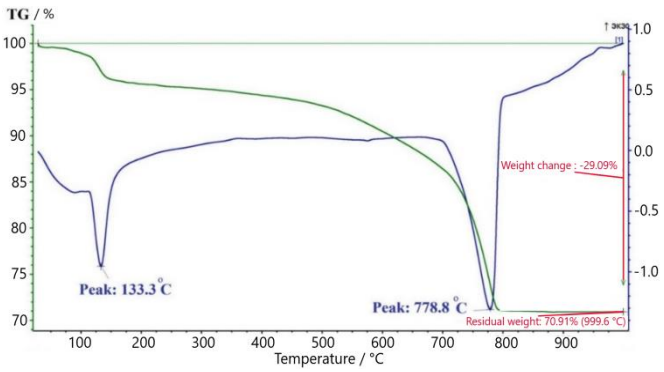

Figure 4. Differential thermal pattern of binder from the screening of concrete waste

The isobaric thermogravimetry curve of $Ca(OH)_2$ exhibits two-stage losses at 585°C dehydration and transition to CaO: First, water is extracted from $Ca(OH)_2$, and then CO_2 is extracted from the calcium carbonate impurity. It is well known that highly basic C-S-H (II) calcium hydrosilicates, as opposed to low-basic C-S-H (I) hydrosilicates, are stable in a saturated lime solution media. The aforementioned fibrous calcium hydrosilicates of the C-S-H (II) group are therefore the most significant binding component of concrete waste.

Although the current study is a study of the thermal effects on concrete waste up to 600°C, the variables were examined at higher temperatures up to 1000°C. The decarbonization of weakly crystallized metastable forms of calcium carbonate ($CaCO_3$) that resulted from the partial carbonization of calcium hydroxide is mostly responsible for the modest endo effects at 690°C and 715°C. These effects appearing in the DTA test are the variables that occur in the concrete waste and which reflect their properties on the binder from the screening of concrete waste after grinding and rehydration.

According to research on the variables that occur in concrete waste when it is burned at temperatures as elevated as 600°C, no changes were found in the characteristics that would specifically impact the rehydration process of binder obtained from the screening of concrete waste. It is known that the hydration process in cement mixtures using Portland cement is not more than 75 %, and therefore, there is a large amount of unhydrated cement grains that contain mineral compounds C_3S and C_2S. These compounds are responsible for the rehydration and thus hardening process, which can be obtained and reworked using the grinding of concrete waste [21]. The differential thermal analysis of concrete waste revealed that temperature has an impact at temperatures of 900°C and higher. C_3S and C_2S undergo polymorphism changes starting at temperatures of 920°C and above. Therefore, the mineral components that cause hydration and the mixture's resistance gain are unaffected by the burning temperatures (400°C and 600°C) applied in this study.

3.2 Heat dissipation

Thermal stress and irregularities in the thermal field within concrete structures are important factors influencing the structural integrity of massive concrete and reinforced concrete components, which are important during the construction phase, as they form the basis for evaluating resistance to thermal cracking [13, 14]. The temperature resulting from hydration reactions plays an important role in the operational properties of the concrete structure and also in determining the life of the structure due to the significant effect on the development of cracks in the concrete structure.

Table 4. Thermal performance of binders from the screening of concrete waste

SSA (m^2/kg)	Binder	t_{sr} (s)	Exo Effect			Max. H_d in 72 Hours (J/g)
			MOA (hr: min: sec)	Max. Value (J/g.h)	H_d (J/g)	
300-350	control binder	15	00:04:17	50.71	1.43	168.5
			08:36:00	10.17	58.81	
	binder exposed to 400°C	17	00:04:37	50.13	1.75	163.5
			09:12:00	12.15	71	
	binder exposed to 600°C	18	00:06:33	48.33	1.63	160.3
			10:23:00	09.36	68	

MOA: Moment of achievement, t_{sr}: start of reaction, H_d: dissipation heat

The results of the thermal differential test of the binder supported the findings of the investigation into the efficacy of hydration reactions. The heat emissions from hydration processes between the binder subjected to burning and the binder not exposed to burning did not differ significantly, according to the data. In this study, the binder from the screening of concrete waste, exposed to burning, was involved to investigate these challenges. Table 4 provides a detailed

thermal analysis of the cementitious binder systems at different combustion temperatures. Based on the results, it can be concluded that there are no significant differences between all samples in the heat release resulting from the binder hydration processes, confirming the results of previous tests.

3.3 Compressive strength and density

The results in Figure 5 and Table 5 represent samples cast from the binder fired at 400 and 600°C and the unfired reference mix aged 3, 7 and 28 days, after the samples were removed from the water and heated to 80°C for 15 minutes to achieve a constant moisture condition. The results indicated that the density reached 2327 kg/m³ and the compressive strength was 11.5 MPa for the reference (unburned) binder. This is attributed to the hydration of the binder and the formation of a denser microstructure, thus greater compressive strength due to fewer pores and closer grains. However, the density remained almost unchanged in the samples burned at 400 and 600°C, but was accompanied by a decrease in density and compressive strength. This is due to the combustion of organic materials and the disintegration of the internal structure of the samples, with the appearance of pores at 600°C. This is explained by the thermal differential test of the binder resulting from concrete waste fragments, which indicates that the material retains crystal water between 550-600°C, after which endothermic reactions and loss of crystal water begin. When heating continues further, the sintering stage begins and the grains become closer to each other due to phase transformations resulting from chemical reactions between the oxides that make up the mixture. This results in a significant increase in density and mechanical strength [20].

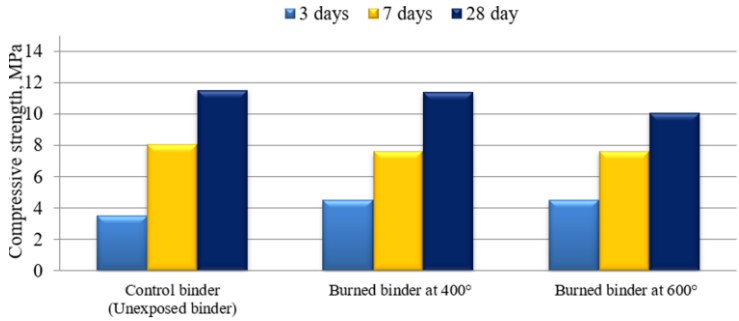

Figure 5. Compressive strength results

Table 5. Influence of burning on compressive strength

T_{bur} (°C)	W/C	Setting time		SSA m^2/kg	Compressive Strength, MPa			Den. (m^3/kg)
		t_{sr} (min)	t_{nd} (min)		3 (d)	7 (d)	28 (d)	
Non burn	0.37	125	165	350	3.5	8	11.5	2327
400	0.37	146	215	350	4.5	7.6	11.4	2320
600	0.37	149	217	350	4.5	7.6	10.1	2320

t_{sr}: start of reaction, t_{nd}: end of reaction, Den.: density

3.4 Shrinkage and expansion deformations

Shrinkage and expansion characteristics are important for binders obtained from screening concrete waste. This helps study the structural behavior of these materials at advanced ages, and also provides insight into structural failures caused by humidity and temperature conditions. Rapid changes in humidity can lead to cracks or damage to the structures. The results confirmed the compatibility with the results of previous tests. Therefore, the samples were promptly put in a standard hardening chamber with an air temperature of 18-20°C and a relative humidity of up to 95% after the shrinkage and expansion deformations for binders were evaluated. Measurements were carried out to evaluate sample deformations and changes in moisture content after two days of normal hardening. Studies were carried out at 3, 7, 14, 28, 60, and 90 days to examine for changes in moisture content and sample deformations. Figure 6 shows the test results.

In the first stage, swelling is almost equal in all binders, reaching its highest value at the age of seven days. Then, the deformation goes towards zero and the second stage of deformation begins. The next stage of deformity begins at about ten days of age. The second stage of deformation is shrinkage deformation, which extends to the end of the test. The behavior of the binders at this stage is almost similar throughout the test time. From the results of test, it can be noted that the behavior of the binders was not affected by burning at temperatures of 400°C and 600°C. This is consistent with the results of previous tests, and this is due to the fact that the minerals responsible for the hydration reactions and thus the volumetric changes change at temperatures above 900°C.

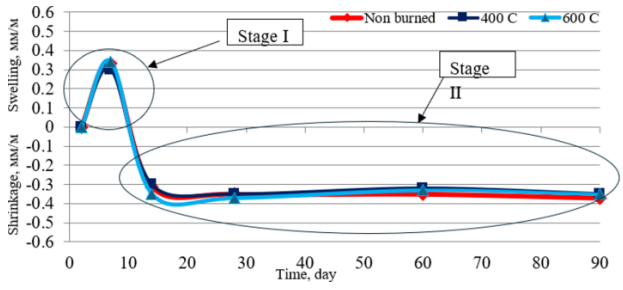

Figure 6. Shrinkage and expansion deformities of binders

3.5 Microstructure study (SEM)

Using scanning electron microscopy (MIRA 3 LMU), the microstructure of the concrete samples was thoroughly investigated. The morphological characteristics and phase composition of the samples obtained from burned and unburned binder were analyzed. The SEM results correlated well with the observed compressive strength trends, indicating

a relationship between the microstructural refinement and the mechanical performance of the mixtures. Key morphological features are summarized in Figures 7-8, which compares the microstructure of the control mix (non-burned) with samples exposed to burning with 400℃ and 600℃.

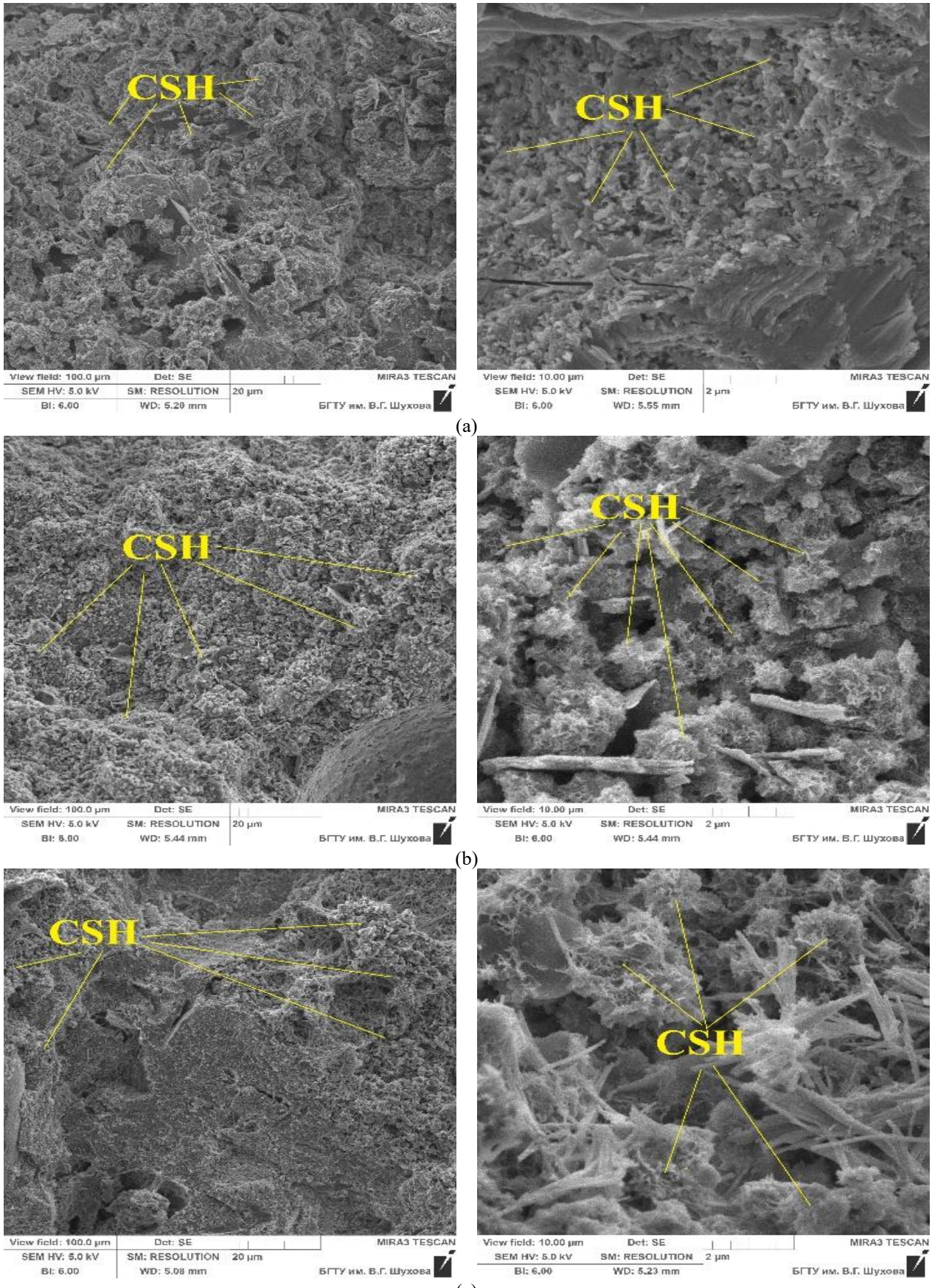

Figure 7. Microstructural features of binder mixtures at 3 days: (a) Control binder; (b) Binder exposed to 400℃; (c) Binder exposed to 600℃

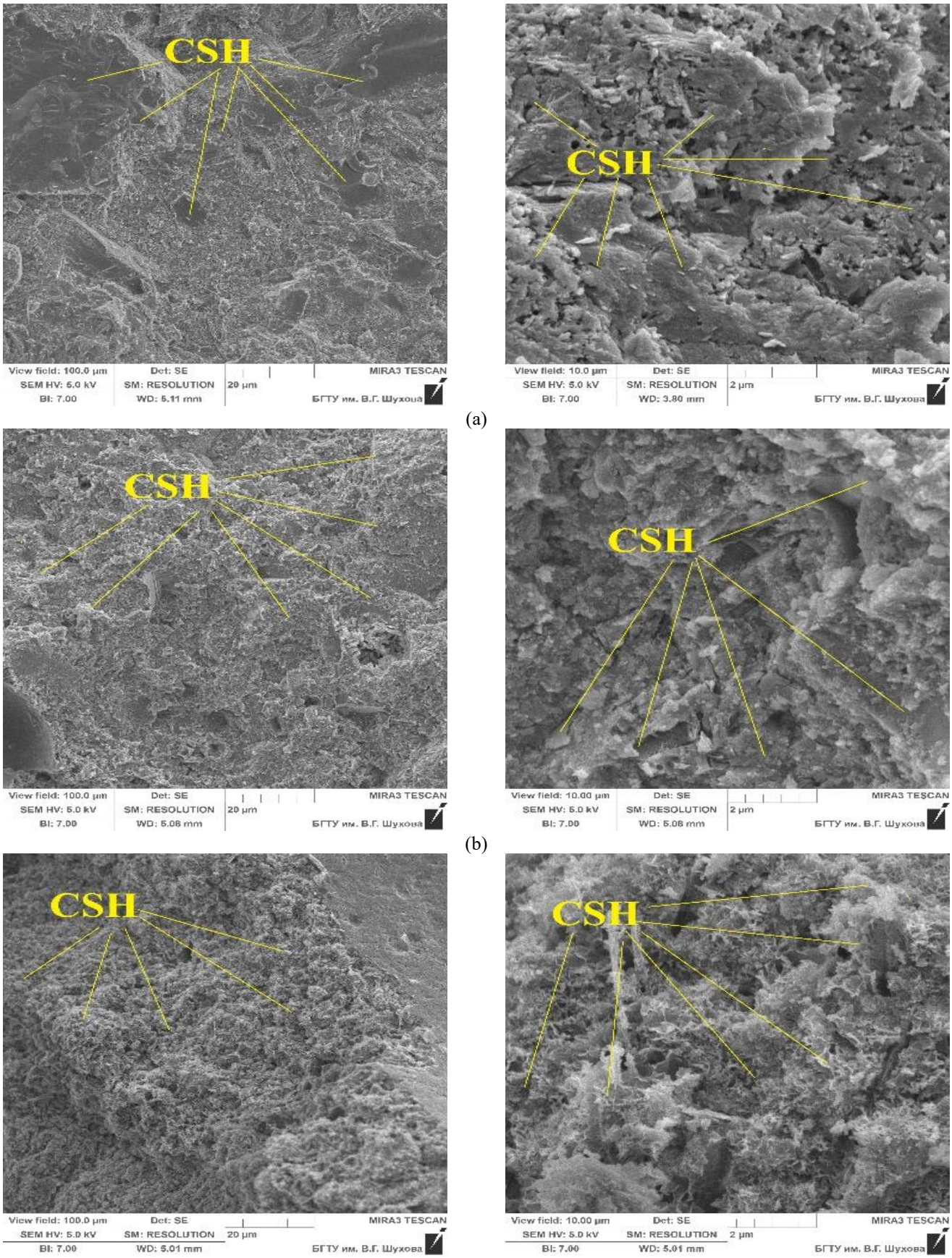

Figure 8. Microstructural features of binder mixtures at 28 days: (a) Control binder; (b) Binder exposed to 400°C; (c) Binder exposed to 600°C

It is clear from the figures that the behavior of the microstructure of all samples during the hydration and aging process is a normal behavior and does not differ in the samples obtained from the binder exposed to burning from the control samples. The density of the internal structure of the samples increases with age and it is also possible to observe the

disappearance of pores, thus obtaining a more homogeneous structure with age and for all samples.

Microscopic examination of the samples reveals the consistent presence of calcium silicate hydrate (C-S-H), the primary product of hydration reactions, across all ages. Furthermore, the microstructural features of the investigated specimens exhibit no significant deviation from those of the reference sample. With the progression of hydration, a gradual enhancement in structural integrity is observed, reaching its highest level at 28 days. These microstructural observations are in full agreement with the outcomes of the mechanical tests, thereby reinforcing the validity of the experimental data.

4. CONCLUSIONS

The main conclusions of the present study could be summarized as follows:

•The results of the compression test showed that the changes resulting from burning the binder at a temperature of 400℃ and 600℃ are slight and do not have a significant effect on the compressive strength of all samples resulting from the binder produced from concrete waste.

•All samples exhibit normal microstructure during the hydration and aging processes, and the samples from the binder exposed to burning do not differ from the control samples in any way. As samples age, their internal structure becomes denser and pores can be seen to disappear, resulting in a more uniform structure over time and across all samples.

•The results of the thermal differential analysis showed that the burning effect occurs at temperatures above 700℃. The variables were investigated at higher temperatures up to 1000℃, even though the current study only looks at the thermal impacts on concrete waste up to 600℃. The mild endo effects at 690℃ and 715℃ are primarily caused by the decarbonization of weakly crystallized metastable forms of calcium carbonate ($CaCO_3$) that were produced as a result of the partial carbonization of calcium hydroxide. The variables that arise in the concrete waste and that show their qualities on the binder from the screening of concrete waste during reworking after grinding and rehydration are the impacts that show up in the thermal differential test.

•Swelling and shrinking are the stages of deformation that continue till the test is over. Over the course of the test, the binders behave in nearly the same manner. It can be observed from the test results that burning at 400℃ and 600℃ had no effect on the binder's behavior. This is because at temperatures higher than 900℃, the minerals that cause the hydration processes and, consequently, the volumetric changes.

•Finally, it can be concluded from the current study that concrete waste resulting from the burning and demolition of structures and buildings can be used in the manufacture of active compounds and binding materials, as long as the building's burning temperature (if the building is exposed to burning during demolition, such as military operations and others) does not exceed 600℃.

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