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PROPERTIES OF BLASTFURNACE CEMENTS (CEM III/A, B, C) BASED ON PORTLAND CEMENT CLINKER, BLASTFURNACE SLAG AND CEMENT KILN DUSTS

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ABSTRACT

This study has examined the effectiveness of characteristically different cement kiln dusts (CKDs) as a partial replacement for the ground granulated blastfurnace slag (GGBFS) in the development and production of three types of blastfurnace cements (CEM III/A, B, C) according to the standard EN 197-1. 27 CEM III cement blends, 9 blends per type of cement, i.e., CEM III/A, CEM III/B and CEM III/C, were prepared in the laboratory mill from industrial starting materials (Portland cement clinker, gypsum, GGBFS, CKDs). The addition of gypsum as the setting regulator was fixed at 4 mass % in all blends studied. The content of both CKDs (cement clinker dust and cement filter dust) as slag replacements was 4 mass % in all CKD blends studied. The ordinary Portland cement (OPC) type CEM I 42.5N was used as the control cement. The results have shown that the chemical composition and chemical and physical properties of prepared CEM III/A, B, C cement blends meet the EN 197-1 requirements. Strength development in these cement blends is obviously related to the Portland cement clinker-to-GGBFS ratio. When compared to OPC, the blastfurnace cement developed lower compressive strength at early ages, but equal or higher at later ages in more cases, i.e., all 9 CEM III/A and 7 CEM III/B cement blends meet, while no CEM III/C cement blend meets the EN 197-1 requirements for standard compressive strength Class 42.5N. From the perspective of strength, the presence of the cement clinker dust is more effective than that of the cement filter dust due to their different chemical and mineralogical compositions.

Keywords: Blastfurnace cement (CEM III/A, B, C), GGBFS, CKDs, chemical and physical properties, mechanical strength, mortars

1. Introduction

Ground granulated blastfurnace slag (GGBFS), obtained as a by-product in the production of metallic iron, is granulated, rapidly cooled, and therefore predominantly glassy, basic slag. The slag contains the same oxides (SiO_2, Al_2O_3, CaO) that make up Portland cement but in different proportions. According to the European cements standard EN 197-1, at least two-thirds of the slag by mass must be glass and the mass ratio (CaO+MgO)/SiO_2 must also be greater than 1.0 [1]. The latent hydraulic properties of slag are activated in the presence of cement clinker, sulphates or calcium hydroxide (but other alkaline substances are also effective). With all activators, the calcium silicate hydrate or C–S–H phase is produced as the hydration product which governs the hardening. Clinker activation is used in the manufacture of Portland slag cements and blastfurnace cement, and sulphate activation in the manufacture of super sulphate cement. Generally, the rate of hardening of slag cement is somewhat slower than that of ordinary Portland cement (OPC) during the first 28 days, but increases thereafter so that at 12 months the strength becomes close to or even exceeds that of OPC [2]. GGBFS can be used as a direct replacement for OPC on one-to-one basis by mass. Replacement rates for GGBFS vary from 30 mass % to up to 85 mass %. In general, up to 50 mass % GGBFS is used in most applications. However, higher replacement rates up to 85 mass % GGBFS are used in special applications either to improve the durability of concrete in aggressive environments or to reduce heat of hydration in massive concrete structures [3]. Nowadays the GGBFS is most widely used as the main constituent to produce high-performance Portland cement blends that are more economical and environmentally friendly. The EN 197-1 differentiates some main categories of cements containing different proportions of GGBFS, i.e., Portland slag cement (CEM II), Blastfurnace cement (CEM III) and Composite cement (CEM V). The Portland slag cement type (CEM II) exists in two classes designated as CEM II/A–S and CEM II/B–S in which the maximum content of GGBFS is 20 and 35 mass %, respectively. There are two classes of Composite cements CEM V designated as CEM V/A and CEM V/B in which, in addition to cement clinker and pozzolana, the maximum content of GGBFS is 30 and 50 mass %, respectively. Blastfurnace cements CEM III (where CEM III is the designation for three types of blastfurnace cements A, B and C), in addition to Portland cement clinker, contain between 36 and 95 mass % of GGBFS with subdivisions at 66−80 mass % of GGBFS [1]. Table 1 shows the composition of three types of blastfurnace cements (BFSC).

Table 1 Composition of blastfurnace cements (BFSC) [1]

According to EN 197-1, chemical requirements for blastfurnace cements CEM III/A, B, C limit the content of loss on ignition (LOI), insoluble residue (IR), sulphate (as SO_3), and chloride to 5.0 mass %, 5.0 mass %, 4.0 mass %, and 0.1 mass %, respectively. The alkali content (expressed as Na_2O-equivalent) is limited to the maximum value of (0.95−1.10), 2.00, and 2.00 mass % for CEM III/A, CEM III/B and CEM III/C, respectively. The specific surface area must be not less than 4000 cm^2/g. The expansion in Le Chatelier test for soundness must not exceed 10 mm [1].

Cement kiln dusts (CKDs) are finely divided particulate materials which have been produced and carried on by combustion gases as a result of the movement of materials through the kiln system during the production of Portland cement, and collected by the control device system (e.g., cyclone, bag house, or electrostatic precipitator). The physical, chemical and mineralogical composition of CKD is determined by raw feed used to produce clinker, type of kiln operation and fuel, and individual plant practices including the dust collection system. With the exception of CKD collected from cement kiln exhaust gases, all the dusts have the same chemical composition as the raw feed [2]. Cement kiln dust is composed primarily of variable mixtures of calcined and non-calcined feed materials, fine cement clinker, fuel combustion by-products, and alkali compounds. The relatively high alkali (Na_2O and K_2O) and sulphate content of CKD is the predominant factor preventing its direct recycling with cement raw materials in the kiln during cement production. Therefore, the use of CKDs in cement mortars and concrete, as a potential replacement for either ordinary Portland cement (OPC) or for blastfurnace slag cement (BFSC) is more effective [3-5]. In general, wide variations observed in the chemical composition of CKDs limit their possible applications. The presence of alkali, sulphate and free lime in CKDs may play an important role in activation of aluminosilicate-containing materials, such as fly ash or slag, when CKDs are used in blended cements [6]. The European cement standard EN 197-1 allows the use of inorganic material substances from clinker production as a minor additional constituent to cement up to 5 mass % [1].

The utilization of CKDs in blended cements was a subject of many studies. Bhatty [7] investigated the effectiveness of cement kiln dust (CKD) in blended cement systems using ordinary Portland cement (OPC), five different CKDs, two different types of fly ash (Class F and C), and GGBFS. He found that cements containing CKD alone had reduced strength, setting time, and workability, while the addition of fly ash to a CKD-OPC system lowered the alkali content and resulted in improved strength. Shoaib et al. [8] evaluated the effect of partial replacement (10, 20, 30, and 40 mass %) of "untreated" raw CKD, collected from electrostatic precipitators, on mechanical properties of OPC, BFSC and sulphate resisting Portland cement (SRPC). The authors found that the optimum quantity of CKD replacement which could be used in the manufacture of these types of cements was not more than 30 mass %, 20 mass % and 10 mass % for SRPC, BFSC and OPC, respectively. Heikal et al. [9] investigated the effect of the partial replacement (2.5, 5.0, 7.5 and 10.0 mass %) of by-pass cement dust on physical and rheological properties of Portland cement clinker-GGBFS composites. Three blends of slag cements were prepared with Portland cement clinker-to-GGBFS ratios of 70/30, 50/50, and 30/70, respectively. The authors found that by-pass cement dust, which contained high amounts of alkalis (3.32 mass %) and CaO (42.99 mass %), affected physical and rheological properties of Portland cement clinker-GGBFS composites both by its content and mix composition. The addition of 2.5 mass % by-pass cement dust to blends containing up to 50 mass % GGBFS retarded initial and final times and accelerated the final setting times of blend containing 70 mass % GGBFS. With the addition of 5.0 mass % by-pass cement dust to blend containing 70 mass % GGBFS the initial and final setting times were extended. Higher additions of by-pass cement dust (from 7.5 to 10.0 mass %) accelerated the final setting times. According to these authors, this may be due to the increased amount of excess alkalis in by-pass cement dust, which acts as a good activator for the hydration of the hydraulic latent GGBFS. Namely, during alkaline activation, the network structure of GGBFS disintegrated and silicate and aluminate ions were taken into the solution, which resulted in the increase of the hydration rate. Konsta-Gdoutos and Shah [10] investigated the possibility of utilizing CKDs from different sources as an activator of

GGBFS in terms of hydration products, time of setting, rates of heat evolution and strength development. The authors reported that the combination of both chemical and physical characteristics of CKDs was critical in controlling the mechanisms of GGBFS activation, the properties of hydration products, and the strength development rate. Maslehuddin et al. [11] evaluated the effect of 0, 5, 10 and 15 mass % CKD replacements on the compressive strength development and durability characteristics of the ASTM C 150 Type I (ordinary Portland cement) and Type V (high sulphate resistance cement) cements. According to authors, the limit value of CKD replacement is 5 mass % from the aspect of both durability and strength. Higher CKD replacements (10 and 15 mass %) affected chloride permeability and electrical resistively, suggesting the risk of reinforcement corrosion. Amin et al. [12] studied the effect of calcined CKD content and the calcination temperature on the hydration properties of GGBFS. They concluded that the activation of GGBFS increased with the increasing content and calcination temperature of the CKD. A similar conclusion was reached in a study conducted by El-Didamony et al. [13]. The authors found that the activation of GGBFS increased with the firing temperature of kiln dust and the amount of added anhydrite. Kiln dust (calcined at 1300 ^{o}C) with the addition of 15 mass % of anhydrite was found to be suitable for the production of super sulphate cement. Abo-El-Enein et al. [14] investigated the effect of CKD and kiln meal additions on strength development of the BFSC. They found that both additions accelerated the hydration rate but lowered compressive strength when compared to BFSC.

The present research is the first attempt to investigate the effectiveness of characteristically different cement kiln dusts (CKDs) that were used as a partial replacement for the GGBFS in both the development and manufacture of three types of blastfurnace cements CEM III/A, B, C according to the EN 197-1 standard. Physical and chemical, and mechanical characteristics of these blends were studied with respect to the normal consistency and setting times, soundness, and mechanical strength. The optimum compositions suitable for the production of CEM III/A, B, C cements containing CKDs (the EN-197 standard strength Class 42.5) were established.

2. Experimental procedure

2.1. Materials

Materials used in this research were a Portland cement clinker and two different types of CKDs (supplied from the Kakanj Cement Works, Heidelberg Cement Group**,** Kakanj, B&H), granulated blastfurnace slag (obtained from the BH Steel Arcelor Mittal Zenica, B&H), and gypsum (provided from the Komar Gypsum Plant, Donji Vakuf, B&H). Very fine powders of both untreated raw CKD or filter dust (herein referred as CFD), whose composition corresponded to non-calcined feed materials, and clinker dust (herein referred as CKD), which consisted predominantly of cement clinker materials, were collected by a bag house from the raw mill and the clinker cooler, respectively. The mineralogical composition of Portland cement clinker, determined by electron microscopy (EM Olympus BX 51), was 65.5 mass % C_3S, 9.4 mass % C_2S, 9.2 mass % C_3A and 11.0 mass % C_4AF. In addition to clinker minerals, it contained periclase (MgO), lime (CaO), and arcanite (K_2SO_4) in the proportion of 4.9 mass %. X-ray diffraction (XRD) analysis (Fig. 1) indicated that the granulated blastfurnace slag (GGBFS) consisted of 90 mass % of glassy phase [15]. The chemical composition of materials used was determined by X-ray fluorescence (XRF) spectroscopy (Philips Cubix XRF with Super Q Program), and are shown in Table 2.

Figure 1 XRD plots of materials used in this study: GGBFS (black plot), filter dust (blue plot), Portland cement clinker (red plot), and clinker kiln dust (green plot) **[15].**

Table 2 Chemical analysis of materials used (in mass %)

2.2. Specimens and testing

According to the EN 197-1 standard, CEM III/A, B, C 42.5N blastfurnace cement (BFSC) blends were prepared. The content of GGBFS and Portland cement clinker varied between 35 and 91 mass %, and between 5 and 57 mass %, respectively. The content of gypsum as the setting regulator was fixed at 4 mass % in all blends studied. The GGBFS replacement by both CKDs (cement clinker dust and cement filter dust) was 4 mass % in all CKD blends studied. 27 CEM III/A, B, C blends, 9 blends for each of three types of the BFSC, were prepared. CEM III/A, CEM III/B and CEM III/C blends were designated U1 ... U9, U10 ... U18, and U19 ... U27, respectively. Ordinary Portland cement (OPC), type CEM I 42.5N, containing 96 mass % of Portland cement clinker and 4 mass % of gypsum, was used as the control cement. Cement mixture proportions (in mass %) as well as the chemical composition of the control OPC and all three types of CEM III/A, B, C 42.5N blends are shown in Tables 3, 4, 5 and 6, respectively.

The laboratory-prepared CEM III/A, B, C blends were produced by inter-grinding cement clinker with GGBFS and the addition of gypsum, and either CKD or CFD in the ball mill to the Blaine fineness of 4300 cm^2/g [16]**.** As expected, the grinding ability of GGBFS is lower than that of clinker, i.e., by increasing the slag content in BFSC blends, the time of grinding increases. For example, in 2.0 kg BFSC blends the time of grinding increases from 130 min to 160 min and to 185 min for CEM III/A, CEM III/B and CEM III/C blends, respectively. The specific gravity of all prepared cement blends, determined by pycnometer, was about (in g/cm^3): 3.10, 2.78−2.92 (average value 2.85), 2.69−2.76 (average value 2.72), and 2.61−2.68 (average value 2.64) for the control OPC, CEM III/A, CEM III/B and CEM III/C, respectively.

Physical and chemical properties (the required water for normal consistency and Vicat setting time, Le Chatelier volume expansion) of all CEM III/A, B, C cement blends were determined in accordance with the standards of EN 196-3 [17]**.** Three series of CEM III/A, B, C mortar samples and one control CEM I 42.5N mortar sample (40 x 40 x 160 mm in size) with water-to-binder ratio of 0.5 were prepared in accordance with the standards of EN 196-1 [18]**.** Compressive and flexural strength development tests were carried out on mortar specimens in accordance with the EN 196-1 standard [18] from triplicate specimens at the age of 2, 7, 28, 90, 180 and 365 days. All the reported results are the averages of three measurements.

Table 3 Mixture proportion of control, ordinary Portland cement (OPC), CEM I 42.5N, and blastfurnace cement, CEM III/A 42.5N, in mass %

Table 4 Mixture proportion of blastfurnace cement, CEM III/B 42.5N, in mass %

Table 5 Mixture proportion of blastfurnace cement, CEM III/C 42.5N, in mass %

Table 6 Chemical composition of control, ordinary Portland cement (OPC), CEM I 42.5N, and three types of blastfurnace cements CEM III/A, B, C prepared (where samples designated as U1 ... U9, U10 ... U18, and U19 ... U27 denote the CEM III/A, CEM III/B and CEM III/C, respectively), in mass %.

3. Results and discussion

3.1. Chemical and physical properties

The chemical composition of materials used as well as of the control OPC (CEM I 42.5N) and three types of blastfurnace cements CEM III/A, B, C prepared are shown in Tables 2 and 6, respectively. Results given in Table 2 indicate that GGBFS used contained, in addition to CaO and MgO, significant amounts of SiO_2 as a main constituent, but it met the requirements of EN 197-1, i.e., the mass ratio (CaO+MgO)/SiO_2 was greater than 1.0. Contrary to OPC, by increasing the GGBFS content in CEM III/A, B, C the content of SiO_2 and MgO increased but the CaO content decreased. The clinker dust (CKD) collected from the cleaning system of clinker cooler generally differs in composition from the filter dust (CFD) that corresponds to the raw meals only in its degree of calcination. Similar to Portland cement clinker, CKD contained significant amounts of CaO (66.66 mass %) compared to CFD (43.21 mass % CaO). Table 6 shows the chemical analysis and characteristic values (loss on ignition, insoluble residue, sulphate content as SO_3, alkali content as Na_2O-equivalent, and chloride content) of the control OPC (CEM I 42.5 N), and CEM III/A, B, C blends, determined according to EN 196-2 [19]. In all 27 BFSC blends the average content of loss on ignition, insoluble residue, sulphate content as SO_3, alkali content as Na_2O-equivalent, and chloride content was (in mass %): 1.81, 0.0024, 2.92, 0.40, and between 0.0014 and 0.0042, respectively. These values are lower than the values specified by EN 197-1 [1].

The water requirement for standard consistency and setting times of control OPC (CEM I 42.5N) and CEM III/A, B, C blends are shown in Figures 2 and 3, respectively. An average value of the water requirement for all the 27 BFSC blends were varied in range of 26.0 to 28.2 % compared with 27.0 % for control OPC. This indicates that GGBFS affected the consistency of BFSC and it decreased with increased in GGBFS content from 61 to 76 mass % (U1 and U10 blends). However, by increasing of the GGBFS content to 91 mass % (U19 blend), the consistency increased (Fig. 2). The results show that addition of cement filter dust (CFD) slightly decreased the water requirements for normal consistency when compared to the cement clinker dust (CKD). The lower water requirements were noted in the U9, U17 and U25 blends, i.e., in blends which, in addition to cement clinker, gypsum and CFD, contain 46, 64 and 87 mass % GGBFS, respectively. The higher water requirements was noted in the U14 and U24 blends, i.e., in blends which, in addition to cement clinker, gypsum and CKD, contain 64 and 82 mass % GGBFS, respectively. The initial and final setting times of OPC (CEM I 42.5N) and CEM III/A, B, C are showing in Fig. 3. The OPC reached initial set in

130 min whereas for the CEM III blends it was extended on average values of 211 min, 223 min, and 220 min for CEM III/A, CEM III/B, and CEM III/C, respectively. The average values of final setting time in OPC and CEM III/A, B, C blends were 170, 279, 287, and 284 min, respectively. Significant increase in the final setting time, between 300 and 325 min, was observed for the BFSC blends containing CFD (i.e., U7, U9, U16, and U18 blends). As expected, the OPC (CEM I 42.5N) reached final setting time after 40 min of the initial set, whereas for the CEM III/A, CEM III/B and CEM III/C blends were extended on 67.8 min, 64 min and 64 min, respectively. The increase in the initial and final setting time with the decreasing of the water requirements for normal consistency in the BFSC-CFD blends indicates a low hydraulic properties (low CaO content) of CFD in comparison with cement clinker dust (CKD). The Le Chatelier volume expansion test was shown values of 0.5 mm for all BFSC blends expect the U6, U9 and U12 blends with values of 3.0, 1.0 and 1.0 mm, respectively. However, all obtained values were within the allowable value of 10 mm specified by EN 197-1 [1].

Figure 2 Water required for standard consistency for all analysed cement blends.

Figure 3 Initial and setting times for all analysed cement blends.

3.2. Mechanical strength development

The development of compressive strength as a function of hydration time (2−365 days) of the control OPC mortar (CEM I 42.5N) and CEM III/A, B, C mortar blends is shown in Figures 4(a)−4(c). Generally, it can be seen that the compressive strength increases gradually with the curing time for all mortar samples. When compared to the OPC mortar, CEM III/A, B, C mortars show lower compressive strength during the first 28 days, but after that their strength increases considerably, so that at 12 months it becomes close to or even exceeds that of OPC.

The CEM III/A blend with the clinker-to-GGBFS ratio of 46/50 and with the addition of 4.0 mass % of gypsum (the U3 sample) developed the highest 365-day compressive strength of 87.60 MPa when compared to the OPC strength of 75.20 MPa and to all BFSC blends. The BFSC blends with 4.0 mass % of gypsum, the clinker-to-GGBFS ratio of 57/35 and the addition of either 4.0 mass % of CKD (the U5 sample) or 4.0 mass % of CFD (the U8 sample) reach higher values of the 365-day compressive strength, in the range of 85.60 MPa and 80.20 MPa, respectively, than the OPC mortar (75.20 MPa). However, at the age of 28 days, the compressive strength of all CEM III/A blends was lower, ranging from 45.80 MPa to 60.00 MPa, when compared to the control OPC strength of 66.90 MPa. These values, however, meet standard strength for Class 42.5, which stipulates the standard 28-day strength of cement in the range between 42.5 MPa (minimum) and 62.5 MPa (maximum), as defined in EN 197-1. When compared to OPC, the increase of the GGBFS content in CEM III/B blends results in the lowering of both 28- and 365-day compressive strength, but the values obtained meet, in most cases, the standard strength for Class 42.5. For example, with the clinker-to-GGBFS ratio in the range between 28/68 and 28/64, the U11, U14 and U17 mortar samples developed strength ranging from 43.60 MPa to 70.20 MPa, 46.60 MPa to 73.10 MPa, and 40,00 MPa to 59.60 MPa at the age from 28 to 365 days, respectively. The compressive strength development of all CEM III/C blends was always lower than that of OPC and of CEM III/A, B blends and did not meet standard requirements for the strength Class 42.5. For example, with the clinker-to-GGBFS ratio in the range between 14/82 and 14/78, the U20, U23 and U26 mortar samples developed strength ranging from 31.30 MPa to 46.60 MPa, 36.10 MPa to 54.70 MPa, and 28.10 MPa to 40.20 MPa at the age from 28 to 365 days, respectively. The above results indicate that all 9 CEM III/A and 7 CEM III/B cement blends meet the EN 197-1 requirements in terms of compressive strength, i.e., the EN-197 standard strength Class 42.5, while no CEM III/C cement blend meets these requirements.

Alternatively, these CEM III/B and CEM III/C blends may be utilized to produce low early blastfurnace cements [20].

Figure 4(a) Compressive strength development of control CEM I cement mortar and U1-U9 (CEM III/A) cement mortar blends.

Figure 4(b) Compressive strength development of control CEM I cement mortar and U10-U18 (CEM III/B) cement mortar blends.

Figure 4(c) Compressive strength development of control CEM I cement mortar and U19-U27 (CEM III/C) cement mortar blends.

A similar trend due to different proportions of the cement clinker-to-GGBFS ratio and curing time was also observed in the development of flexural strength, as shown in Figures 5(a)−5(c). Compared to OPC (the standard flexural strength at 28 days of 5.5 MPa), flexural strength of all BFSC blends was lower at early ages (2 and 7 days), but equal or higher at later ages (up to 28 days). For example, the flexural strength of the OPC, CEM III/A, CEM III/B and CEM III/C was 6.8 MPa, 3.9−5.7 MPa, 3.6−4.4 MPa, and 2.9−3.8 MPa at 7 days, 8.4 MPa, 6.9−8.9 MPa, 7.5−8.2 MPa, and 5.3−9.4 MPa at 28 days, and 9.8 MPa, 9.3−10.8 MPa, 9.4−10.5 MPa, and 8.1−9.9 MPa at 365 days, respectively. When compared to the 28-day compressive strength of the same mortar samples (e.g., the U2, U5, U8 and U9 blends), the flexural strength of these mortars was higher than that of the OPC mortar, Figs. 4(a) and 5(a). Specifically, the addition of CFD had a more significant effect on the flexural strength development than the CKD addition even in the case of a higher GGBFS content of 46.0 mass % (the U9 mortar sample).

Figure 5(a) Flexural strength development of control CEM I cement mortar and U1-U9 (CEM III/A) cement mortar blends.

Figure 5(b) Flexural strength development of control CEM I cement mortar and U10-U18 (CEM III/B) cement mortar blends.

Figure 5(c) Flexural strength development of control CEM I cement mortar and U19-U27 (CEM III/C) cement mortar blends

From the results obtained it can be concluded that the strength development is obviously related to the GGBFS content, i.e., to the clinker-to-GGBFS ratio. The CEM III/A mortars, which contain between 35 and 61 mass % GGBFS, show equal or higher strengths than the control OPC mortar after 180 and 365 days of hydration. However, as the GGBFS content increases (e.g., in the range between 64−76 mass % and 78−91 mass % in CEM III/B and CEM III/C blends, respectively) with the decreasing cement clinker content (e.g., in the range between 20−28 mass % and 5−14 mass % in CEM III/B and CEM III/C blends, respectively) the compressive strength decreases. So, CEM III/C blends have a lower early and late strength than the specified values. This indicates that cement clinker is mainly responsible for strength development, i.e., the initial reaction of hydration is governed by the clinker fraction in the BFSC. Moreover, the formation of nuclei of the calcium silicate hydrate or C–S–H phases which have a higher CaO/SiO_2 ratio and are capable of growth (and can only be produced in the presence of hydrating C_3S or cement clinker) have a certain importance in the activation effect on slag. On the other hand, the hydration mechanism of a combination of GGBFS and either Portland cement or Portland cement clinker is slightly more complex than that of Portland cement or clinker alone. The hydration reaction involves the activation of GGBFS by alkalis and sulphates to form its own hydration products. During its hydration, GGBFS in BFSC consumes a varying proportion of $Ca(OH)_2$ produced during the hydration of the cement clinker fraction. The main hydration product of GGBFS is hydrated calcium silicate, as the C–S–H gel, which is different from that formed in the Portland cement clinker hydration and has a lower CaO/SiO_2 ratio which decreases with the increasing slag content.

For this reason it is justifiable to differentiate a latent hydraulic reaction, in which the consumption of $Ca(OH)_2$ is of secondary importance only, and a pozzolanic reaction [2].

The results obtained in this study indicate that with the proper mix design, i.e., the clinker-to-GGBFS ratio, both CKDs (cement clinker dust, CKD, and cement filter dust, CFD) can be successfully utilized as a replacement for GGBFS. Generally, the replacement of GGBFS by CKD is more effective than the replacement by CFD. A possible explanation could be that CFD (which by composition corresponds to cement raw meals, i.e., non-calcined feed materials) acts mainly like a relatively inert diluent with its fine particles acting as fillers and possibly serving as crystallization nuclei [10]. In contrast to CFD, CKD (which consists predominantly of cement clinker materials) promotes the formation of hydration products and hardening, and acts as an activator for latent GGBFS.

In general, the results in this study show that the direct replacement of GGBFS by CKDs is more effective than the direct recycling of dust with cement raw materials in kiln. CKD utilized as an activator for latent GGBFS in the production of environmentally efficient blastfurnace cements favours efforts towards sustainable development in cement and concrete industry. Moreover, a study on the technical and environmental assessment of the development and production of CEM III/A, B, C blastfurnace cements, as described in this work, confirmed their cost-effective production due to lower required amounts of cement clinker and energy, which at the same time conserves natural resources and reduces CO_2 emissions, when compared to Portland composite cement, which in addition to 65 mass % cement clinker, contains calcareous fly ash (the EN 197-1 cement type CEM II/B–W, the standard strength classes 32.5N and 42.5N) [15].

4 Conclusions

The obtained results for chemical and physical as well as mechanical properties of all three types of blastfurnace cements (CEM III/A, B, C), which have been presented in this study, provide evidence that the CKDs (cement clinker dust or cement filter dust), collected from different sources during the production of Portland cement, can be directly and effectively used as a replacement for GGBFS. With the appropriate mix composition, i.e., the clinker-to-GGBFS ratio, the addition of CKDs can provide satisfactory overall performance regarding chemical requirements, setting time, volume stability, and mechanical properties. Although the addition of GGBFS results in lower strength at early ages, the replacement of Portland cement clinker by GGBFS up to 72 mass %, does not have any negative effect on the compressive strength of concrete after 28 days. Summarizing these experimental results the following conclusions are proposed:

1. When comparing the average values of loss on ignition (1.81 mass %), insoluble residue (0.0024 mass %), sulphate content as SO_3 (2.92 mass %), alkali content as Na_2O-equivalent (0.40 mass %), and chloride content (0.0014−0.0042 mass %), obtained in all 27 BFSC blends (CEM III/A, B, C), with the EN 197-1 limited values (in mass %): 5.0, 0.5, 4.0, between 1.0 and 2.0, and 0.1, respectively, the values obtained meet the chemical requirements for cements. Moreover, the prepared CEM III/A, B, C blends exhibit much lower values then those specified by the standard.

2. The production of blastfurnace cements CEM III/A, B, C standard strength Class 42.5N in accordance with the EN 197-1 requirements is possible for 16 of 27 blends prepared. All 9 CEM III/A blends and 7 CEM III/B blends meet the requirements, and no sample of CEM III/C meets the EN 197-1 requirements for the standard compressive strength Class 42.5N.

3. The strength development of CEM III/A, B, C blends was significantly affected by the CKDs addition. As expected, the presence of the cement clinker dust as an activator for latent GGBFS was more effective than the cement filter dust which acts as a filler due to its low hydraulic reactivity.

4. The direct replacement of GGBFS by CKDs in the production of economical and environmentally efficient blastfurnace cement favours efforts towards sustainable development in cement and concrete industry.

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TABLES:

Table 1 Composition of blastfurnace cements (BFSC) [1]

Types of BFSC	Clinker (mass %)	GGBFS (mass %)	Minor additional constituents (mass %)
CEM III/A	35–64	36–65	0–5
CEM III/B	20–34	66–80	0–5
CEM III/C	5–19	81–95	0–5

Table 2 Chemical analysis of materials used (in mass %)

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
Portland cement clinker	20.88	5.79	3.61	66.24	1.08	0.56	0.54
Gypsum	4.81	1.83	1.51	32.08	1.63	36.14	0.46
Granulated blastfurnace slag	40.51	9.86	0.94	37.75	7.73	0.26	1.22
Cement clinker dust, CKD	22.60	4.41	2.91	66.66	0.95	0.70	0.47
Cement filter dust, CFD	15.82	4.06	2.01	43.21	0.64	0.78	0.57

Table 3 Mixture proportions of control, ordinary Portland cement (OPC), CEM I 42.5N, and blastfurnace cement, CEM III/A 42.5N, in mass %

Samples	Portland cement clinker	Granulated blastfurnace slag	Gypsum	Cement kiln dust	Cement filter dust
OPC	96.00	-	4.00	-	-
U1	35.00	61.00	4.00	-	-
U2	57.00	39.00	4.00	-	-
U3	46.00	50.00	4.00	-	-
U4	35.00	57.00	4.00	4.00	-
U5	57.00	35.00	4.00	4.00	-
U6	46.00	46.00	4.00	4.00	-
U7	35.00	57.00	4.00	-	4.00
U8	57.00	35.00	4.00	-	4.00
U9	46.00	46.00	4.00	-	4.00

Table 4 Mixture proportions of blastfurnace cement, CEM III/B 42.5N, in mass %

Samples	Portland cement clinker	Granulated blastfurnace slag	Gypsum	Cement kiln dust	Cement filter dust
U10	20.00	76.00	4.00	-	-
U11	28.00	68.00	4.00	-	-
U12	24.00	72.00	4.00	-	-
U13	20.00	72.00	4.00	4.00	-
U14	28.00	64.00	4.00	4.00	-
U15	24.00	68.00	4.00	4.00	-
U16	20.00	72.00	4.00	-	4.00
U17	28.00	64.00	4.00	-	4.00
U18	24.00	68.00	4.00	-	4.00

Table 5 Mixture proportions of blastfurnace cement, CEM III/C 42.5N, in mass %

Samples	Portland cement clinker	Granulated blastfurnace slag	Gypsum	Cement kiln dust	Cement filter dust
U19	5.00	91.00	4.00	-	-
U20	14.00	82.00	4.00	-	-
U21	10.0	86.00	4.00	-	-
U22	5.00	87.00	4.00	4.00	-
U23	14.00	78.00	4.00	4.00	-
U24	10.00	82.00	4.00	4.00	-
U25	5.00	87.00	4.00	-	4.00
U26	14.00	78.00	4.00	-	4.00
U27	10.00	82.00	4.00	-	4.00

Table 6 Chemical composition of control, ordinary Portland cement (OPC), CEM I 42.5N, and three types of prepared blastfurnace cements CEM III/A, B, C (where samples designated as U1 ... U9, U10 ... U18, and U19 ... U27 denote CEM III/A, CEM III/B and CEM III/C, respectively), in mass %

Samples	LOI[1]	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O[2]	IR[3]	Cl
OPC	4.87	19.62	5.16	3.41	62.63	1.17	2.07	0.38	0.39	0.0100
CEM III/A										
U1	1.56	31.43	6.31	2.60	49.64	4.50	2.87	0.39	-	-
U2	1.97	27.88	5.85	2.98	53.85	3.60	2.74	0.42	-	-
U3	1.44	29.72	6.05	2.83	52.07	3.98	2.81	0.40	0.36	0.0028
U4	0.45	31.28	6.13	2.72	51.04	4.37	2.92	0.40	-	-
U5	0.76	27.16	5.83	3.11	56.30	3.09	2.66	0.40	-	-
U6	2.64	28.58	5.92	2.85	52.58	3.57	2.76	0.40	0.38	0.0021
U7	3.08	30.83	5.99	2.51	49.31	4.27	2.92	0.39	-	-
U8	4.05	26.54	5.70	2.83	54.05	3.09	2.63	0.41	-	-
U9	2.72	28.88	5.94	2.69	52.11	3.71	2.84	0.41	1.01	0.0031
CEM III/B										
U10	0.42	34.71	6.58	2.29	46.44	5.37	3.09	0.41	-	-
U11	0.31	33.26	6.46	2.56	48.33	4.97	3.00	0.41	-	-
U12	1.83	33.41	6.40	2.41	46.67	5.09	3.08	0.40	0.40	0.0017
U13	1.89	33.51	6.39	2.32	46.63	5.14	3.05	0.38	-	-
U14	2.10	32.00	6.19	2.53	48.41	4.65	3.01	0.40	-	-
U15	1.62	32.91	6.31	2.48	47.71	4.85	3.04	0.39	0.51	0.0021
U16	2.61	33.50	6.35	2.17	46.03	5.20	3.04	0.40	-	-
U17	2.81	32.05	6.23	2.37	47.67	4.76	3.01	0.40	-	-
U18	2.86	32.80	6.21	2.25	46.66	4.97	3.16	0.40	0.99	0.0042
CEM III/C										
U19	1.19	37.47	6.78	2.07	42.36	6.28	2.76	0.40	-	-

U20	1.01	35.78	6.58	2.33	44.54	5.69	2.97	0.40	-	-
U21	1.11	36.58	6.65	2.12	43.66	6.01	2.77	0.41	0.49	0.0014
U22	0.80	36.91	6.70	2.11	43.50	6.03	2.86	0.39	-	-
U23	0.29	35.35	6.48	2.35	45.86	5.55	3.02	0.40	-	-
U24	1.80	35.56	6.43	2.15	44.35	5.71	2.94	0.38	0.42	0.0017
U25	2.53	36.41	6.64	1.85	42.49	6.08	2.92	0.39	-	-
U26	3.08	35.40	6.39	1.84	43.81	5.46	2.85	0.43	-	-
U27	1.92	36.71	6.62	1.89	42.84	5.79	3.08	0.44	0.94	0.0027

[1]Loss of ignition, [2]Na_2O-equivalent, [3]Insoluble residue

Z. Osmanović, N. Haračić, J. Zelić, PROPERTIES OF BLASTFURNACE CEMENTS....

FIGURES:

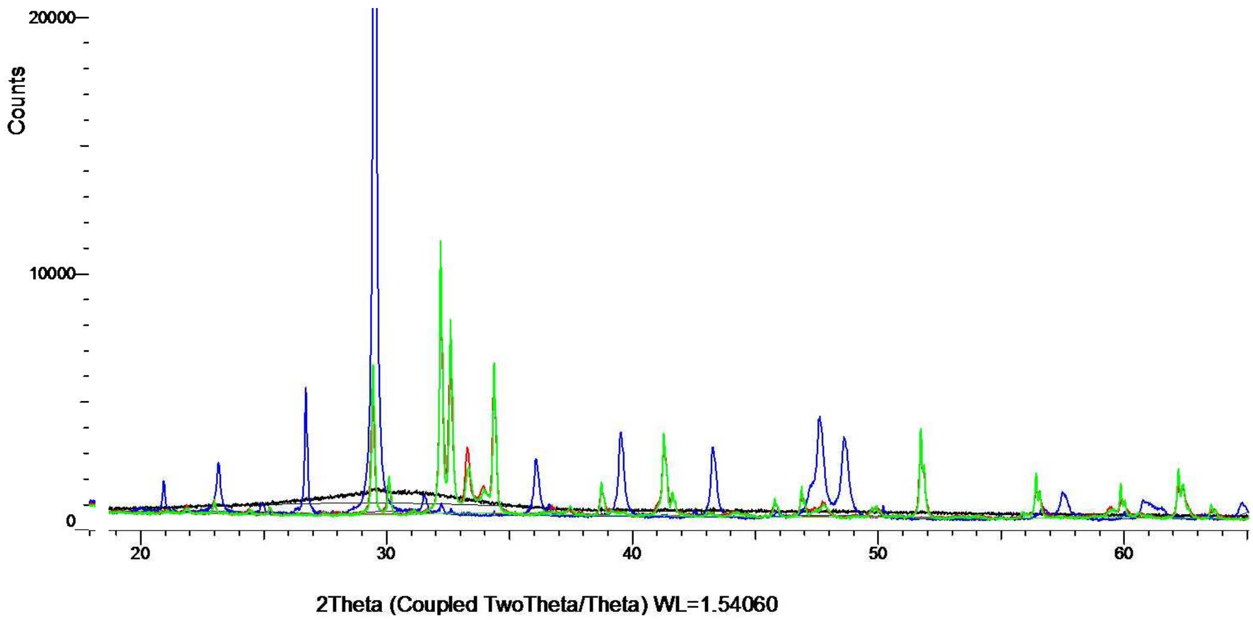


Figure 1 XRD plots of materials used in this study: GGBFS (black plot), filter dust (blue plot), Portland cement clinker (red plot), and clinker kiln dust (green plot) [15].

Figure 2 Water required for standard consistency for all analysed cement blends.

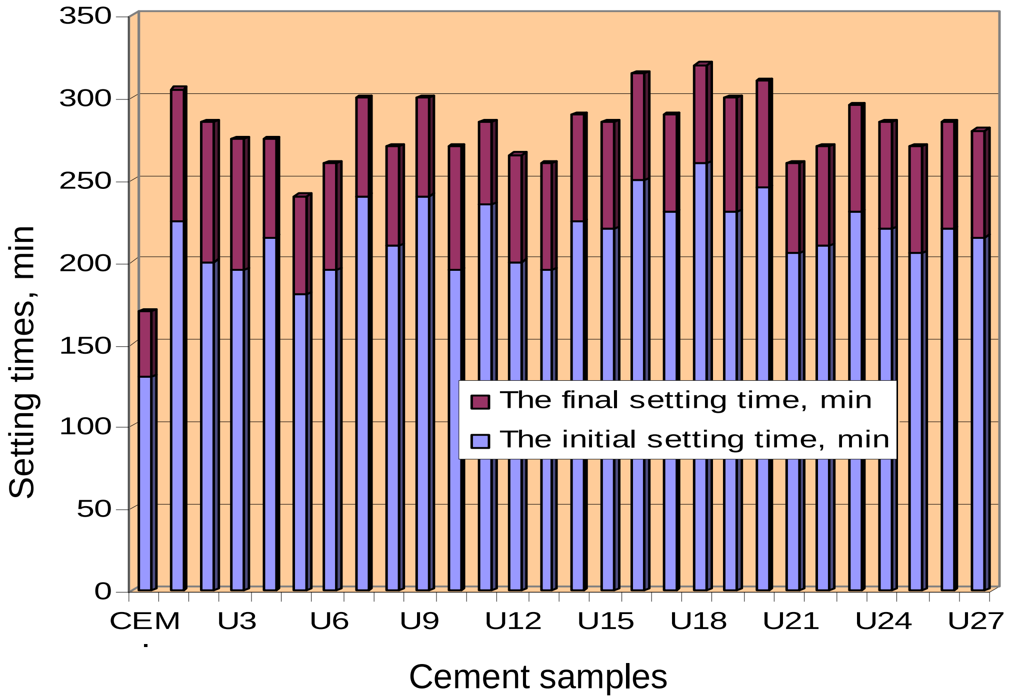


Figure 3 Initial and final setting times for all analysed cement blends.

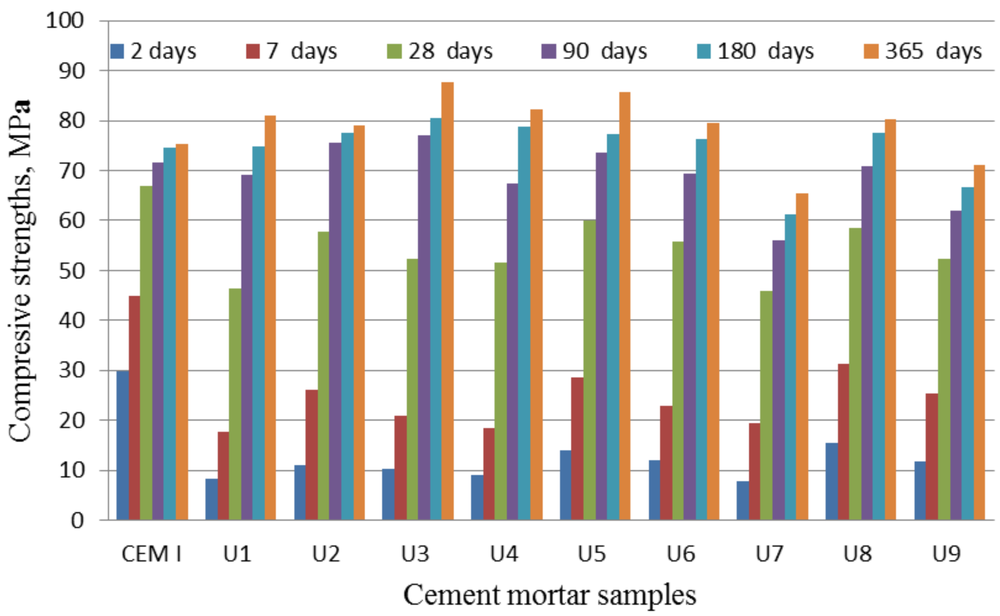


Figure 4(a) Compressive strength development of control CEM I cement mortar and U1-U9 (CEM III/A) cement mortar blends.

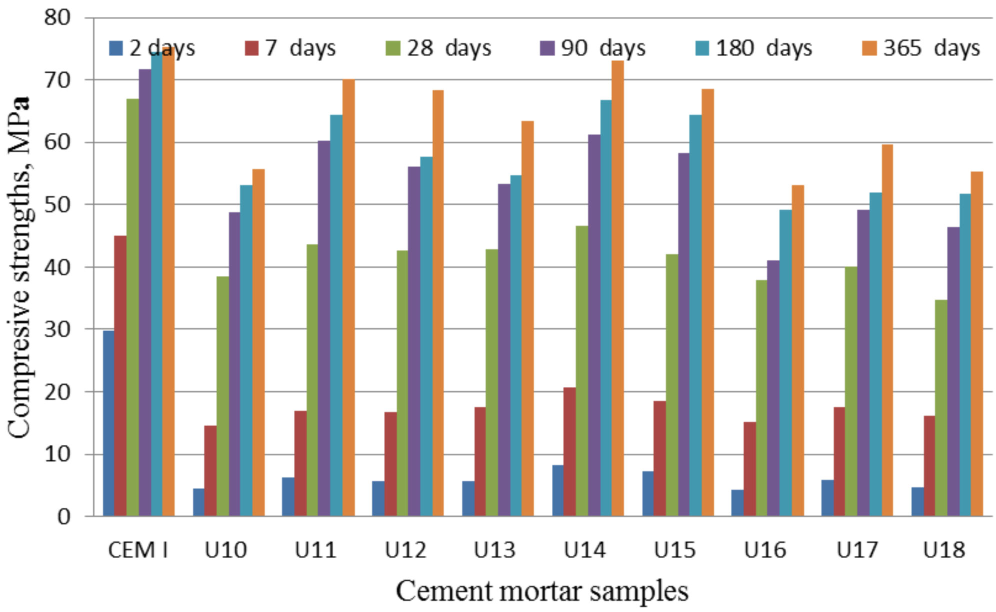


Figure 4(b) Compressive strength development of control CEM I cement mortar and U10-U18 (CEM III/B) cement mortar blends.

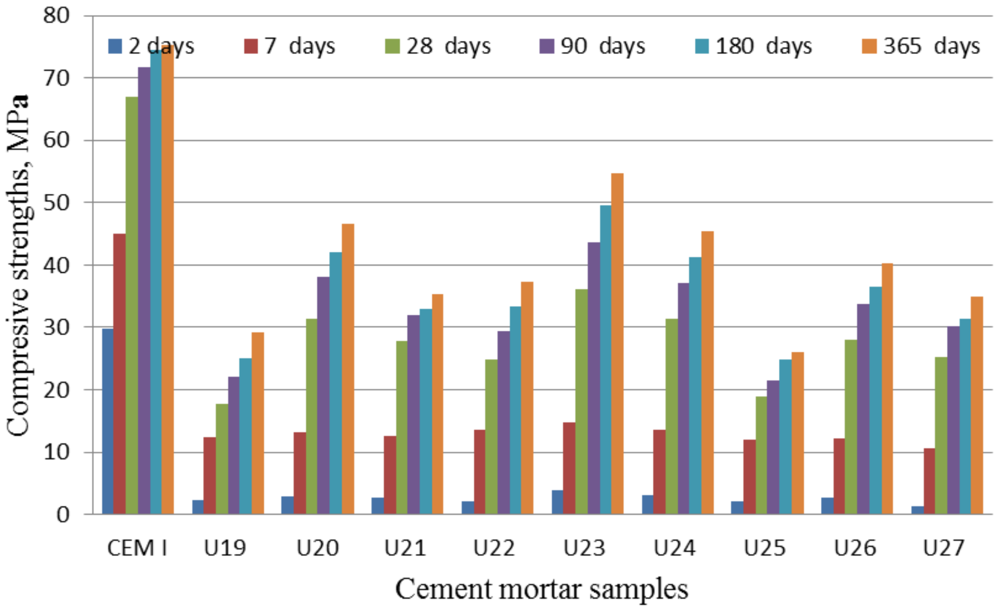


Figure 4(c) Compressive strength development of control CEM I cement mortar and U19-U27 (CEM III/C) cement mortar blends.

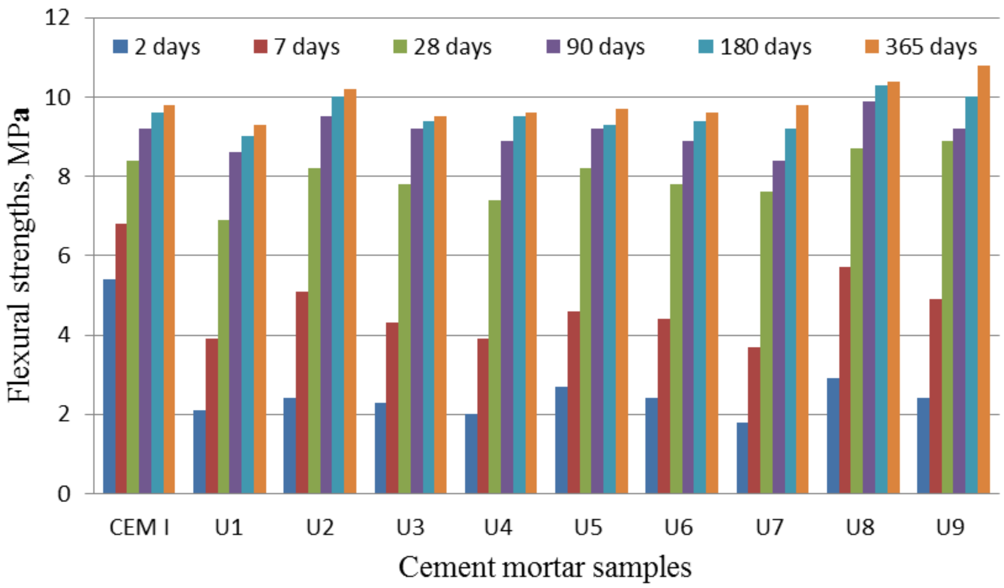


Figure 5(a) Flexural strength development of control CEM I cement mortar and U1-U9 (CEM III/A) cement mortar blends.

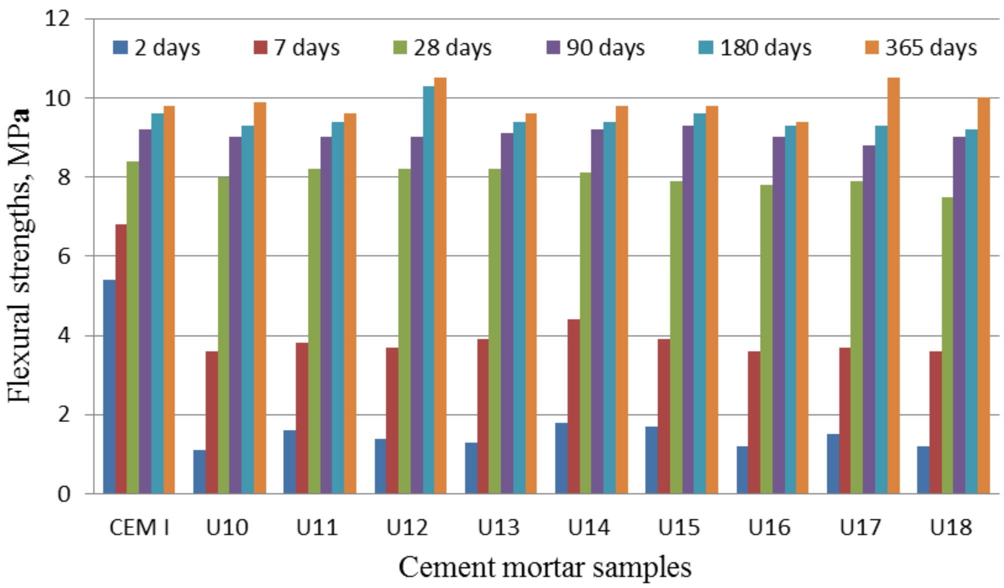
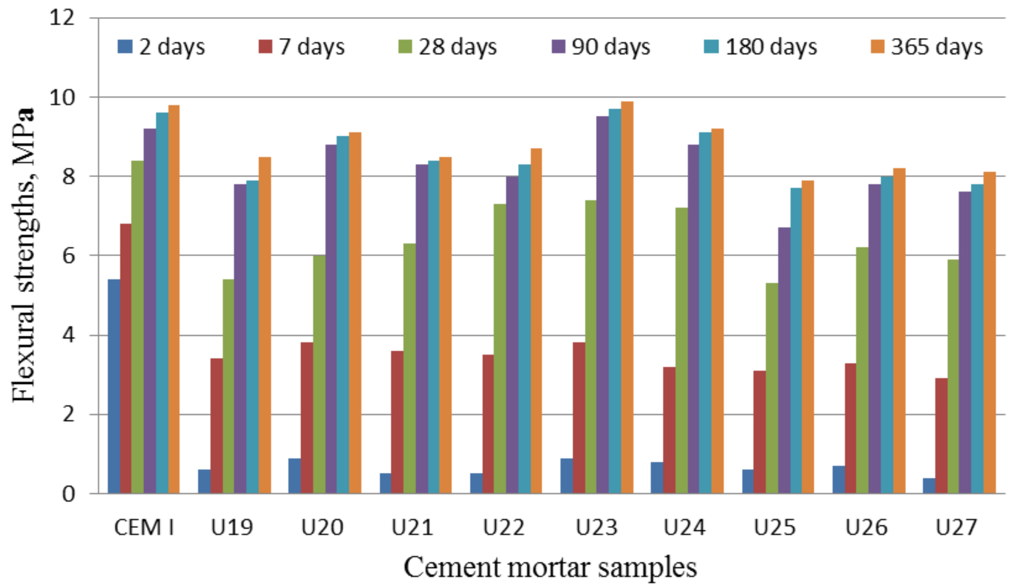


Figure 5(b) Flexural strength development of control CEM I cement mortar and U10-U18 (CEM III/B) cement mortar blends.



1

2 **Figure 5(c)** Flexural strength development of control CEM I cement mortar and
3 U19-U27 (CEM III/C) cement mortar blends.