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Influence of cement kiln dust substitution on the mechanical properties of concrete

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Abstract

Large quantities of cement kiln dust (CKD) are produced during the manufacture of cement clinker by the dry process. The technical and economical problems that arise for the semi-manufacture of raw materials used, energy and transportation of dust from the plant to outside, as well as the severe pollution to the surrounding atmosphere show the necessity of utilizing cement dust as one of the main objectives of our investigation. The cement dust contains a mixture of raw feed as well as calcined materials with some volatile salts. The aim of the present work is to study the effect of cement dust substitution instead of ordinary Portland cement (OPC), blast furnace slag cement (BFSC), and sulphate resistance cement (SRC) on the mechanical properties of some concrete mixes containing them, and also, to determine the optimum quantity of CKD which could be recycled in the manufacture of these types of cements.Useful conclusions and recommendations concerning the use of different amounts of CKD in the production of some blended cements as a partial substitution from different types of cements were obtained.© 2000 Elsevier Science Inc. All rights reserved.

Keywords: Cement kiln dust; Blast furnace slag cement; Acceleration; Bond strength; Calcium silicate hydrate

1. Introduction

In Portland cement manufacture, a mixture of limestone, shale, clay and sand are combined in controlled proportions and ground together either as a dry blend or a water slurry. The ground mixture enters the upper end of the rotary kiln and moves down the kiln toward the burner zone. At high temperature, kiln charge reaches fusion temperature and small-size balls called clinker and also, fine solid particles of the raw material and semi-finish dust are formed [1]. The cement plant's installed dry process generates cement kiln dust (CKD) during the course of operation. This dust contains a mixture of raw feed, partially calcined cement clinker, and condensed volatile salts [2]. Depending on the characteristics of the raw materials and condition of cement manufacture, about 12% of mass of kiln feed exist from the kiln with the gas [3].

The X-ray diffraction analysis of the kiln dust indicates that it consists mainly of limestone as a main component, minor amount of quartz together with $CaSO_4$, NaCl, K_2SO_4, spurite [$2(C_2S)\cdot CaCO_3$] and sulphospurite [$2(C_2S)\cdot CaSO_4$] [4]. The mineralogical constituents of CKD were identified. The role of CKD in some blended cement pastes were studied [5], results of addition of cement dust to either ordinary Portland cement (OPC) or to blast furnace slag cement (BFSC). It was found that the addition of CKD to some blends of OPC, BFSC, and sulphate resistance cement (SRC) have a limit value but with increasing dust value, it has adversely affected the physical and mechanical properties of cement pastes.

The role of volatile alkalies (Na_2O, K_2O) present in dust has also been discussed [6,7], when salts other than sulphates are present, both are preferentially incorporated into C_3A to give orthorhombic form. Na_2O orthorhombic C_3A is retarded in hydration, while K_2O substituted is accelerated. However, when present as sulphates, cement setting can be accelerated and also compressive strength. Alkali-sulphates present can be identified.

The utilization of CKD in the cement industry and building products were studied [8], at which CKD was used as a partial substitute of BFSC, El-Karnak cement, and OPC pastes. Strength development in Portland cement

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pastes with the addition of kiln meal and kiln dust was investigated [9]. The results showed a high degree of hydration and lower compressive strength than the addition of free cement.

The most popular slag cements are Portland BFSC which contain not more than 65% of granulated slag, and OPC clinker with 5–6% gypsum. Portland BFSC has all the physical properties of OPC, but it has much lower heat of hydration and is more sulphate resistant. Compressive strength tests of slag mortars indicate that alkali-activated ground granulated blast furnace slag has potential as a replacement for Portland cement in concrete [10,11]. SRC made from BF slag, $CaSO_4$, small portion of lime and PC clinker, and the SO_3 content must be >5%. It was made by grinding 80–85% slag, to 10–15% anhydrite, and 5% PC clinker [12]. The initial setting and hardening of SRC is associated with the formation of calcium sulpho-aluminate hydrates from slag constituents and the added calcium sulphate [13]. The hydration products of SRC were ettringite ($3CaO{\cdot}Al_2O_3-3CaSO_4-31H_2O$) and CSH [14].

Hydraulic reactivity of blast furnace slag in the presence of Portland cement and $Ca(OH)_2$ was studied by the determination of the degree of hydration of slag and compressive strength of the hardened specimens [15,16]. The hydraulic reactivity was higher for the slag cement mixture than for the slag lime mixture indicating that the coexistence of such materials that liberate Ca^{2+} during its hydration reaction was necessary and effective to improve the hydraulic reactivity of slag. The initial setting and hardening of SRC is associated with the formation of calcium sulpho-aluminate hydrates from the slag constituents and the added calcium sulphate.

The effect of alkaline carbonate is more marked for pozzolanic cement than Portland ones [17]. The accelerating effect of carbonates is considerable not only at 20°C but also at lower temperatures. Nevertheless, they reduce strengths even after 7 days. The effect of potassium salts, including chloride and sulphate on the hydration of alite were studied [20]. It is concluded that the accelerating mechanism of inorganic electrolytes depends on the counter diffusion of Cl^- and OH^- ions, which take place in the CSH surface layer during hydration. The greater the mobility of the anions, the larger the accelerating effect. The large diffusion coefficient of Cl^- ions makes chlorides good accelerators of alite hydration. Formation of alite in the clinker in the presence of alkalies was studied [19]. Alkalies were found to reduce the alite formation, but accelerate the formation of belite.

Generally, direct recycling of CKD in rotary kiln causes a damage in kiln refractories as well as in the formation of phase which has a different hydraulic reactivity. Thus, our study is directed towards the avoidance of the problems due to direct dust recycling and studying the role of alkalies containing dust on activation of slag cements in comparison to OPC; and instead, predicting the optimum dust percent may be used.

2. Materials and experimental program

Materials used in this research are "untreated" raw CKD which were collected from electrostatic precipitators, OPC, BFSC, and SRC which were provided by Suez Cement, Suez, Egypt. The chemical analysis of the materials used in this investigation are given in Table 1.

In this study, a total of 135 cubes and also 135 cylinders were tested to study the effect of replacement of CKD on the mechanical behavior of concrete. The following variables were considered in this study:

1. types of cement (OPC, BFSC, and SRC);
2. percentage of replacement of CKD as ratio to cement used (0%, 10%, 20%, 30% and 40%); and
3. testing period of concrete (1, 3, and 6 months).

Three mixes with three different types of cement were used in this study. The three mixes having the same mix proportions (1 cement: 1.9 sand: 3.52 gravel and 0.5 w/c ratio), and the cement content used in the three mixes was 350 kg/m^3.

The compression and splitting tensile tests were carried out according to B.S. 1881.52 [20], on standard cubes (15 × 15 × 15 cm) and standard cylinders, 15 cm in diameter and 30 cm in height. Three cubes and cylinders were cast from each mix and cured in clean water for 28 days. The crushing load was recorded to determine the compressive strength or tensile strength of concrete sample using universal hydraulic testing machine (Avery-Denison) of capacity 1000 KN.

3. Results and discussion

3.1. Substitution of OPC with CKD

This series deals with the effects of dust substitution to high values on the hydration characteristics and mechanical properties of hardened concrete samples. Previous studies [5] showed that the chemically combined water contents

Table 1
The chemical compositions of materials used

Materials' components	OPC	BFSC	SRC	CKD
SiO_2	21.42	25.8	20.9	11.95
Al_2O_3	3.30	5.25	5.26	1.12
Fe_2O_3	5.23	7.71	4.02	2.45
CaO	62.70	57.4	63.88	49.75
MgO	2.40	2.73	2.50	1.86
SO_3	2.35	3.0	2.36	6.35
S^-	–	1.81	1.95	–
Na_2O	2.41	2.13	0.46	3.87
K_2O	0.45	0.29	0.22	2.66
Cl^-	0	–	–	6.8
Ignition loss	1.22	1.08	0.91	17.92

for OPC pastes substituted with CKD decrease with increasing dust value, this is attributed to the high hydraulic properties of cement phases rather than dust constituents, which is characterized by low or no hydraulic properties. Also, free lime contents decrease with the increase of cement dust in blends; this decrease is mainly attributed to the hydration of the anhydrous phases of cement clinker especially C_3S and C_2S which liberate $Ca(OH)_2$.

The results of ultimate compressive strength (σ_c) and splitting tensile strength (σ_t) of concrete containing OPC with different amounts of cement dust are graphically represented in Fig. 1a, b, c, and d. Generally, it can be seen that compressive strength increases gradually with curing time for all concrete samples. As the hydration proceeds, the amount of hydration products increase, and their accumulation closes the available pore volumes, and this leads to the decrease of total porosity and finally, increases the compressive strength with time.

However, with increasing the amount of replacement CKD as shown in Fig. 1c, the compressive strength decreases. This is due to the replacement of cement clinker, which is mainly responsible for strength development. In addition, the larger amounts of chloride present in cement dust cause a sort of crystallization of hydration products which results in an opening of the pore system of the hardened samples leading to a reduction of strength. Also, dust chloride ions take part in chemical reactions similar to those involving sulphate ions and yield chloro-aluminate hydrate $3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}12H_2O$ which is analogous to $3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O$ [21]. However, the action of chloro-aluminate is different from sulpho-aluminate in that

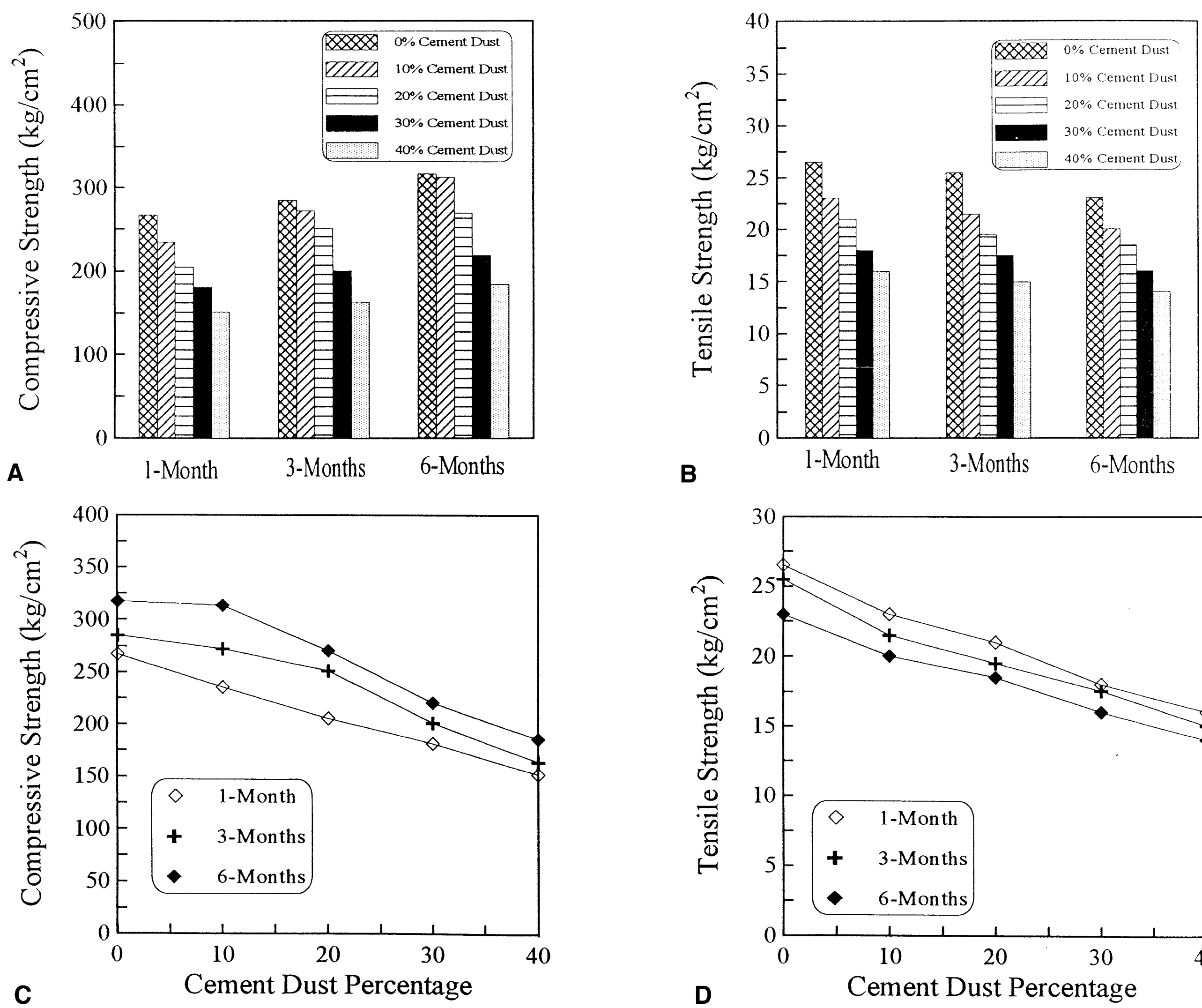

Fig. 1. (a) Effect testing period on the compressive strength of concrete made by OPC. (b) Effect of testing period on the tensile strength of concrete made by OPC. (c) Effect of cement dust percentage on the compressive strength of concrete made by OPC. (d) Effect of cement dust percentage on the tensile strength of concrete made by OPC.

the former does not cause expansion but softening [22]. Also, the presence of alkalies in the cement portion, the microstructure of CSH phases becomes heterogeneous and lowers the ultimate compressive strength [23].

However, tensile stresses are likely to develop in concrete due to drying shrinkage, temperature gradients, and many other reasons. Therefore, the knowledge of tensile strength of concrete is important. Results presented in Fig. 1b and d show a gradual decrease in the splitting tensile strength for all cylinders of concrete samples, this is attributed to the increasing cement dust percentage which does not offer good bond between aggregate and cement mortar-like free OPC hydration phases. Thus, the concrete sample gives a lower bond between the aggregate particles and that lowers tensile strength.

3.2. Substitution of BFSC with CKD

This series is composed of BFSC with different proportions from CKD from 10% to 40% by weight. The influence of replacement of CKD for BFSC on the mechanical properties is graphically plotted in Fig. 2a, b, c, and d. It nearly seems that the addition of CKD which contains lime, alkalies, and sulphates influence the hydration reaction of the slag [24]. Results show an increase in the value of compressive strength with curing time due to the formation, precipitation, and accumulation of hydrated products in water-filled pores to form a more compact body. Generally, the addition of cement dust reduces the compressive strength of concrete samples especially with a high value of substitution, but some of the enhancement in strength for

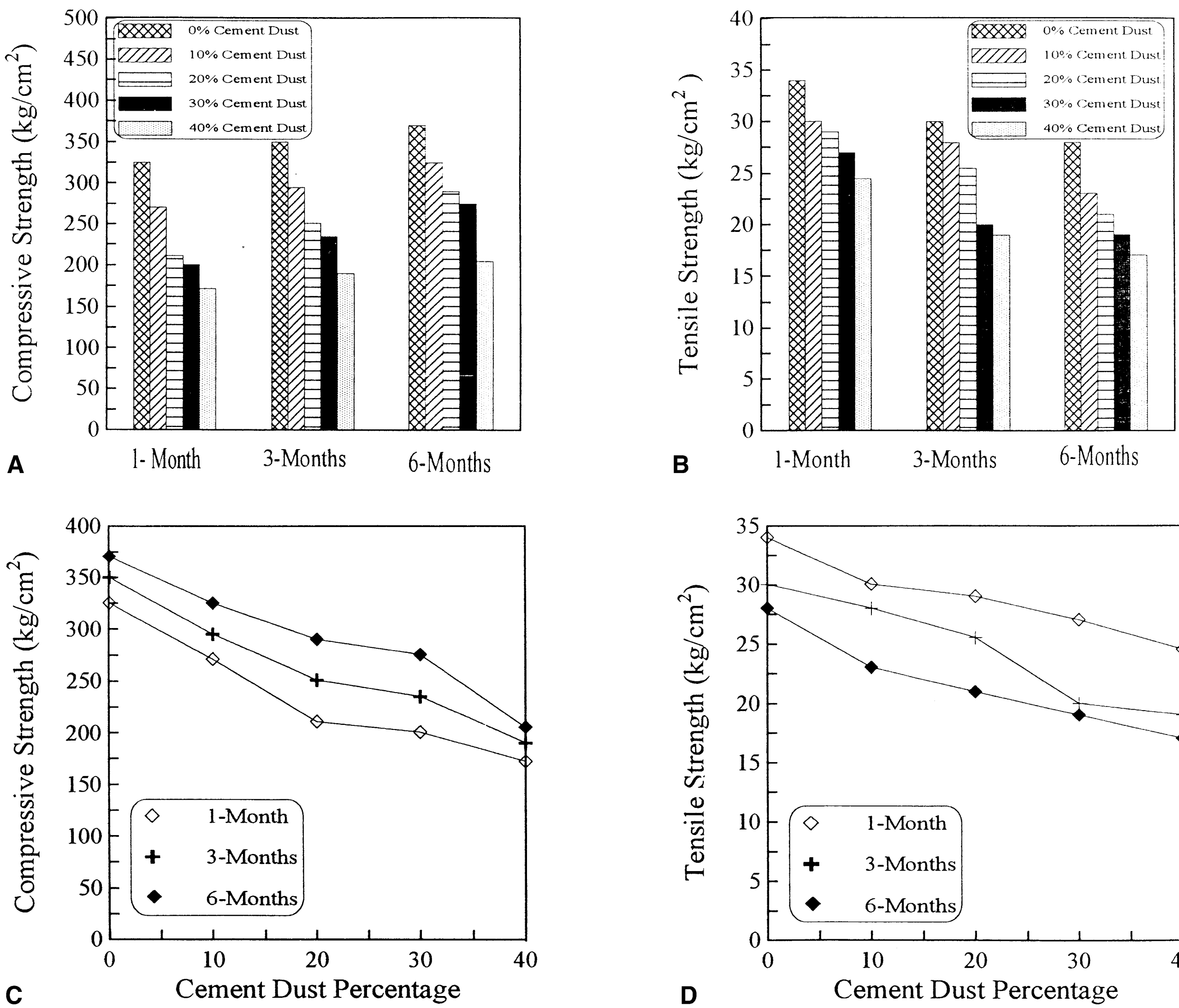

Fig. 2. (a) Effect of testing period on the compressive strength of concrete made by BFSC. (b) Effect of testing period on the tensile strength of concrete made by BFSC. (c) Effect of cement dust replacement on the compressive strength of concrete made by BFSC. (d) Effect of cement dust percentage on the tensile strength of concrete made by BFSC.

samples containing 10% and 20% dust in comparison to strength evaluated due 90% or 80% free cement.

This may be due to the acceleration effect of alkalies and lime containing dust in the activation of slag observed at 3 and 6 months, wherever alkalies increase the solution of silicates and consumption of the hydrated lime by the activated slag to form calcium hydrosilicates or calcium aluminate hydrate with dense structure. The decrease in compressive strength of hardened concrete samples with high values of dust due to the increase of the alkali-sulphates and chlorides, and also due to the decrease of slag and clinker values affecting the amount of CSH and aluminate hydrates, leads to the formation of considerable amounts of hydrated sulpho-aluminates and chloro-aluminates which make expansion and softening, respectively. Results of tensile strength are shown in Fig. 2c and d, indicating that a gradual decrease in tensile strength with time is due to a weakening in cement aggregate bond.

3.3. Substitution of SRC with CKD

Slag-rich cement is characterized by slow rate of reaction and low heat of hydration. When the slag is placed in water alone, it dissolves to a small extent, but a protective film deficient in Ca^{2+} is quickly formed, and inhibits further reaction. Reaction continues if pH is kept sufficiently high. $CaSO_4$ accelerates the reaction of slag glasses, but is not very effective unless a little alkali is also present. Portland cement clinker is added to supply $Ca(OH)_2$ during the setting and hardening period. The target of this series of replacements is to direct the lime and alkali contents of dust in the activation of the slag-rich cement (SRC) and studying

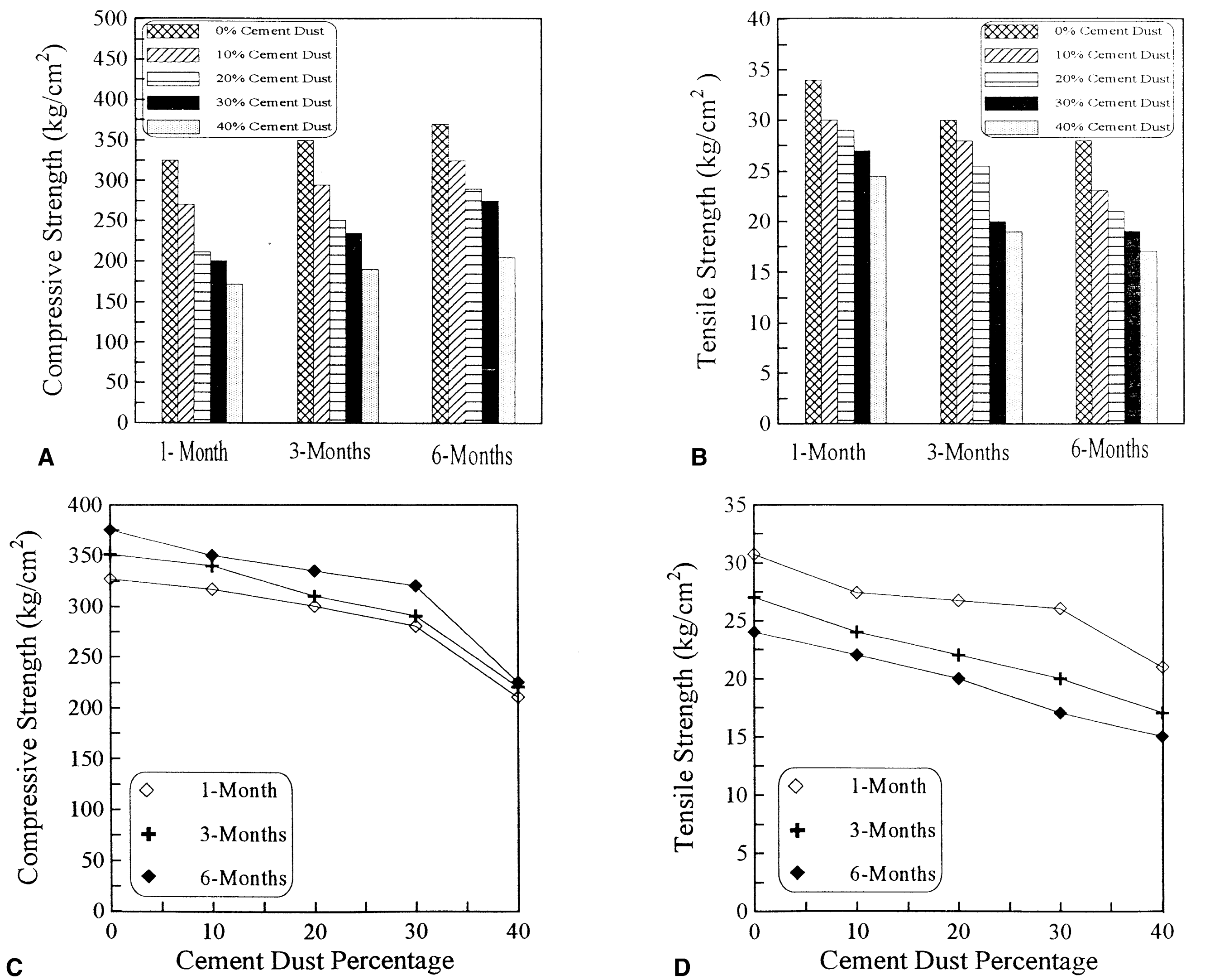

Fig. 3. (a) Effect of testing period on the compressive strength of concrete made by SRC. (b) Effect of testing period on the tensile strength of concrete made by SRC. (c) Effect of cement dust replacement on the compressive strength of concrete made by SRC. (d) Effect of cement dust percentage on the tensile strength of concrete made by SRC.

these effects of substitution on compressive and tensile strengths of concrete containing them.

Results of compressive and tensile strengths for the hardened specimens under investigation cured up to 6 months are graphically represented as a function of curing times in Fig. 3a, b, c, and d. It can be observed that the compressive strength values increase by time for all hardened samples, which is attributed to the formation and accumulation of hydration products with time. The strength development depends primarily on the formation of calcium silicate hydrate (CSH) as the main hydration products. Therefore, the formation of CSH phases with high values of dust will decrease and the strength accordingly decreases, and also, dust containing alkalies which form compounds are low in strength. However, with 20–30% dust value, a relative increase in strength 10% to 18% more than that revealed to 80% and 70% free cement, may be attributed to the acceleration affect of dust, with alkalies, sulphates, chlorides and carbonates compensating the decrease in slag content. Also, due to the formation of large lath-like crystals of ettringite phase at early ages of hydration, this rapid rate of reaction may be due to the activation of slag by the alkalies of cement dust at the late ages of hydration both granular and plate-like CSH is formed filling up the available pore volume; also, calcium carbo-aluminate may be formed due to the presence of calcite in the cement dust composition, especially with high dust values. Results of tensile strength measurements for hardened specimens which is graphically plotted in Fig. 3c and d show the gradual decrease in resisting for shrinkage, thus, lowering tensile strength.

3.4. Effect of cement type on dust substitution

Fig. 4a, b, c, and d gives the relative strengths of OPC, BFSC, and SRC substituted with CKD at interval times 1, 3,

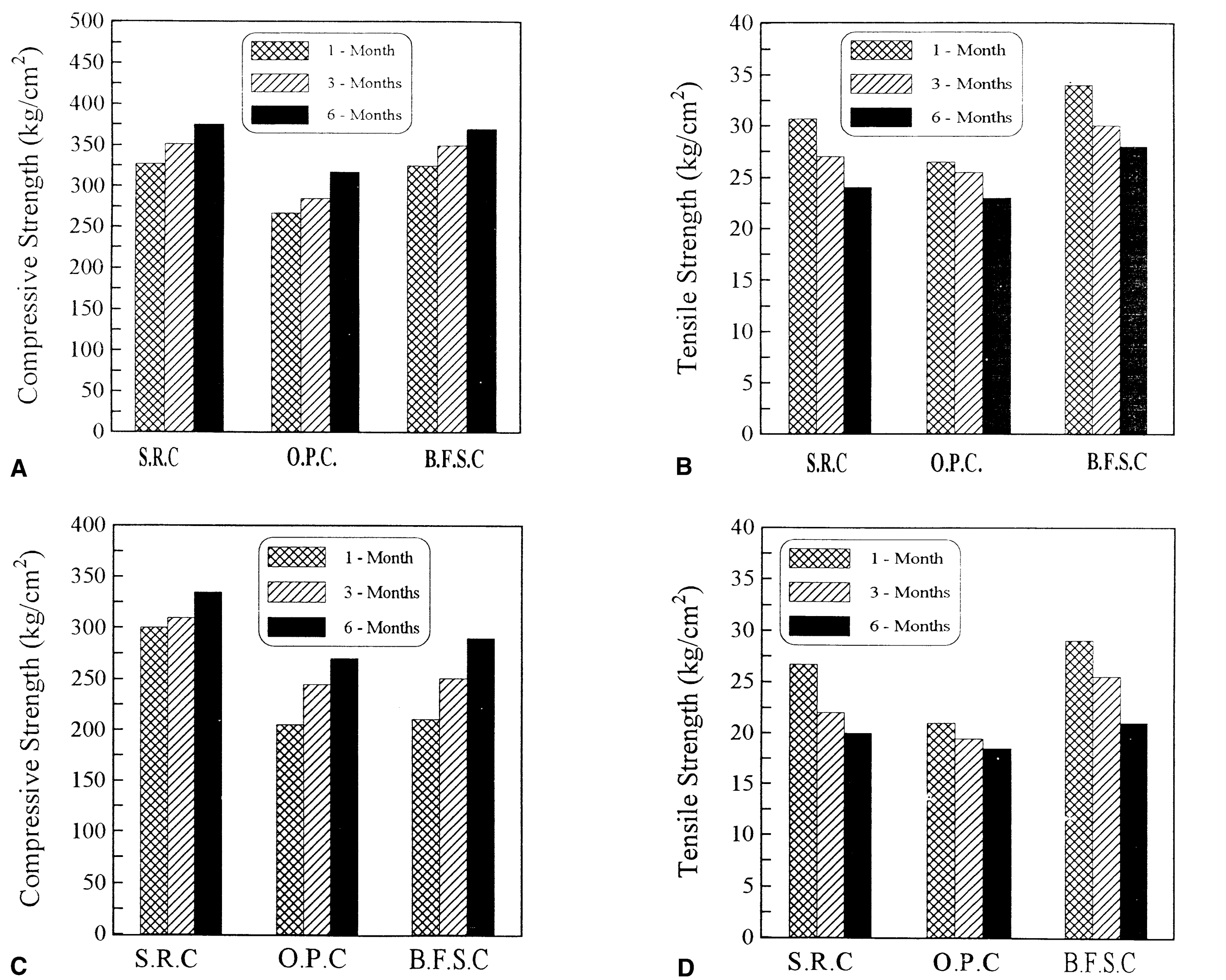

Fig. 4. (a) Effect of type of cement on the compressive strength of concrete made by zero cement dust percentage. (b) Effect of type of cement on the tensile strength of concrete made by zero cement dust percentage. (c) Effect of type of cement on the compressive strength of concrete made by 20% of cement dust replacement. (d) Effect of type of cement on the tensile strength of concrete made by 20% of cement dust replacement.

and 6 months. Results show that SRC which is characterized by high initial strength and a very low heat of hydration at the same time, gives a high strength at ages >28 days. In a comparison with slag cement and OPC, which may be attributed to the high percent of slag containing cement, the dust alkalines have a good effect on activation and enhancing the hydration of slag-containing cement than the OPC only. A good enhancement was observed for 10–20% dust (replacement), ranging from 3% to 15% increase in strength for SRC, less than that of BFSC but with a negative effect for OPC.

4.Conclusion

The present experimentation concerns the influence of dust substitution on the mechanical properties of OPC, BFSC, and SRC, and also the relative strengths depending on each cement type. Results show that with increasing dust percent, generally, the ultimate compressive as well as tensile strengths will decrease for OPC concrete samples; a slight increase in strength were observed for BFSC and some enhancement in concrete sample strengths containing SRC, compared with free cement percent. Also, it was found that the high limit for substitution is not more than 30% for SRC, and 20% for BFSC, and 10% for OPC which gives high ultimate compressive strength for SRC and BFSC, and a critical value for OPC, respectively.

Generally, it could be said that direct replacement (mixing) of CKD with SRC or BFSC is more effective than the recycling of dust with cement raw materials, which forms unfavored clinker phase during the firing in cement kilns, which is attributed to the effect of high alkalinity of dust on the nature of clinker phases.

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