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RESEARCH ARTICLE

Fresh and hardened properties of high-strength concrete incorporating byproduct fine crushed aggregate as partial replacement of natural sand

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ABSTRACT This paper presents the fresh and hardened properties of high-strength concrete comprising byproduct fine crushed aggregates (FCAs) sourced from the crushing of three different types of rocks, namely granophyre, basalt, and granite. The lowest void contents of the combined fine aggregates were observed when 40% to 60% of natural sand is replaced by the FCAs. By the replacement of 40% FCAs, the slump and bleeding of concrete with a water-to-cement ratio of 0.45 decreased by approximately 15% and 50%, respectively, owing to the relatively high fines content of the FCAs. The 28 d compressive strength of concrete was 50 MPa when 40% FCAs were used. The slight decrease in tensile strength from the FCAs is attributed to the flakiness of the particles. The correlations between the splitting tensile and compressive strengths of normal concrete provided in the AS 3600 and ACI 318 design standards are applicable for concrete using the FCAs as partial replacement of sand. The maximum 56 d drying shrinkage is 520 microstrains, which is significantly less than the recommended limit of 1000 microstrains by AS 3600 for concrete. Therefore, the use of these byproduct FCAs can be considered as a sustainable alternative option for the production of high-strength green concrete.

KEYWORDS fine crushed aggregates, quarry dust, compressive strength, splitting tensile strength, drying shrinkage

1 Introduction

Aggregates are fundamental in concrete and is primarily considered as a filler material for economic purposes. However, aggregates significantly affect the properties of concrete, such as strength, stiffness, shrinkage, insulation, durability, and response to high-temperature exposures. Approximately 70% to 80% of the volume of concrete is occupied by aggregates, both in the coarse and fine fractions. The percentage of fine aggregates in concrete typically varies from 35% to 45% of the total volume of aggregates. Consequently, good quality fine aggregates are essential for manufacturing strong, durable, and cost-effective concrete [1]. Natural sand is typically used as the most popular choice of fine aggregate owing to its favorable properties in the production of good-quality concrete. However, increasing the extraction of natural sand from river beds creates serious environmental concerns, such as loss of water retaining sand strata, deepening of the river bed, disturbance to aquatic lives, and lowering of underground water table. Similarly, excessive quarrying of natural sand from mountains increases the risk of landslides and adverse effects on the environment. Therefore, the use of alternative sources of fine aggregates such as quarry rock dust will reduce the extraction of natural sand while affording a safe and environmentally friendly method of their disposal.

Quarry dust is a byproduct of the production of coarse aggregates by the crushing of rocks that must be disposed of safely. The use of fine crushed aggregates (FCAs) or quarry dust as a replacement of natural sand has been recognized by the Green Building Council of Australia [2]. However, the properties of FCAs exhibit high variability and their usage in concrete production is limited. Researchers have shown that the combination of type, shape, texture, grading, and amount of micro fines in

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manufactured sand is critical to ensure the consistency and compressive strength of concrete and mortar [3,4]. Typically, FCAs contains 10% to 20% micro fines, which is significantly higher than that in natural sand. The micro fines may contain deleterious particles such as clay minerals and organic matters, which increase the water demand in concrete [5]. Hence, the micro fines content of natural sand has been limited in many specifications. Hudson [6] stated that FCAs with 15% to 20% micro fines can be used in concrete without negatively affecting the quality of concrete. However, using micro fines in concrete offers several advantages, e.g., excessive bleeding and segregation can be reduced significantly by adding micro fines in the mixture [5]. Considering these early studies, the content of micro fines in natural sand has been limited in many specifications. For example, AS 2758.1 [7] limits the fines content passing through 0.075 mm sieve to 2% for coarse aggregates, 5% for natural fine aggregates, and 20% for manufactured fine aggregates. Provision has been made to use more than 20% micro fines in manufactured sand if the history of successful use is demonstrated. Table 1 shows the limit percentages of micro fines in some countries.

Table 1 Limits of micro fines in different countries [8]

country	micro fines allowed (percentage of crushed sand)
the United States	5% to 7% passing 75 μm sieve
Spain	15% passing 63 μm sieve
England	15% passing 63 μm sieve
India	15% to 20% passing 75 μm sieve
Australia	20% passing 75 μm sieve
France	12% to 18% passing 63 μm sieve depending on purpose of use

The angular shape of FCAs as compared to round natural sand results in a higher void content for the same grading of fine aggregates, as shown by Marek [9]. The study showed that the inclusion of fines did not affect the consistency of concrete. The author explained that the voids were filled by micro fines and water, which were part of the system. However, the micro fines may lubricate the system and offset the reduction in consistency simultaneously owing to the less free water in the mixture. An opposite trend was observed by Çelik and Marar [10], who reported a reduction in slump from using limestone quarry dust of particle size smaller than 75 μm. According to the author, this behavior was observed because more water was required to cover the surface area, which increased with the amount of quarry dust. Similar results were observed by Quiroga et al. [8], where the authors reported an increase in water demand for FCAs with high fines content. In addition, Li et al. [11] showed that using up to 15% of limestone filler increased the consistency and strength of normal strength concrete. However, in high-strength concrete, using up to 7% filler did not affect the workability, whereas a further increase in the amount of filler decreased the slump. Furthermore, Kroh [12] suggested the optimum fines content of 10% when using limestone quarry dust because the consistency improved up to 10% microfines, whereas the use of 15% microfines reduced the consistency. This indicates that up to a 10% microfines content lubricated the matrix and at 15%, the increase in specific surface demanded more water from the paste to wet all the particles, resulting in reduced consistency.

The mechanical properties of concrete with FCAs have been evaluated. Hameed and Sekar [13] reported that quarry dust and marble sludge powder can be used to fully substitute natural sand in concrete. It was reported that the compressive strength and splitting tensile strength of concrete prepared using quarry dust were 14% higher than those of conventional concrete. Ukpata and Ephraim [14] demonstrated that concrete containing mixtures of lateritic sand and FCAs can be reasonably used in concrete manufacturing. Furthermore, Bahoria et al. [15] reported that quarry dust in addition to waste plastic as filler improved the mechanical properties of concrete when used along with superplasticizers. Franklin et al. [16] reported that a 40% replacement of fine aggregates with stone dust improved the compressive strength as compared with the reference concrete. In addition, Singh et al. [17] reported that the inclusion of 40% quarry dust did not affect the compressive strength. Similarly, Cheah et al. [18] reported that the inclusion of quarry dust did not affect the mechanical properties of concrete. However, Gunasekaran et al. [19] showed that the inclusion of quarry dust significantly improved the mechanical properties of concrete, including the compressive strength, flexural strength, splitting tensile strength, and impact resistance of concrete.

From the discussion above, it can be seen that contradictions exist among researchers regarding the optimum content of quarry dust in concrete and mortar, primarily because of the difference in the characteristics of quarry dust used in different studies. Hence, FCAs from different sources must be investigated to evaluate their feasibility. The FCAs used in this study were sourced from three different quarries and their effects on the concrete properties were investigated. First, standard tests related to material characterization were performed to evaluate the feasibility of the FCAs based on AS 2758.1 [7]. Subsequently, a comparative study was performed among the FCAs to investigate fresh concrete properties, such as workability and bleeding; and hardened concrete properties, such as compressive strength, tensile strength, and correlation of strength properties, as per concrete design standards. The effects of the FCAs on the drying shrinkage of concrete were also evaluated.

2 Experiments

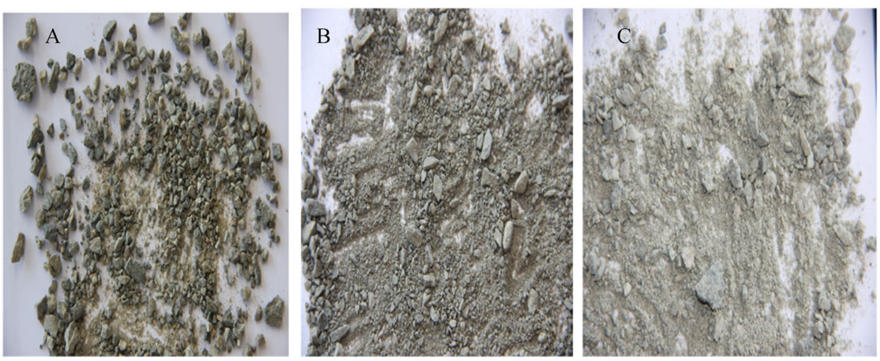
2.1 Characterization of FCAs

Three different FCAs were selected from different locations in Western Australia for this study. The types of source rock were granophyre (A), basalt (B), and granite (C). The FCAs comprised particles of varying shapes and textures. A commercially available natural sand from Western Australia was used as the reference fine aggregate. Figure 1 shows the physical appearances of these three types of FCAs. As shown, higher proportions of fines appeared in FCA types B and C than in FCA type A. Moreover, FCA type B exhibited more elongated and flaky particles. FCA type A had a rougher texture than the other two types.

The physical appearance of the natural sand used is shown in Fig. 2. The sand particles were approximately spherical in shape and were more uniform in size than the FCAs. The physical properties of the FCAs and natural sand are listed in Table 2. As shown, the apparent, dry, and saturated surface dry (SSD) particle density of the FCAs were similar to those of natural sand. However, the water absorption of the FCAs was generally higher than that of the natural sand.

Figures 3(a) and 3(b) show the particle size distributions of FCA types A, B, C and natural sand, respectively. The recommended upper and lower limits from AS 2758.1 [7] are also plotted in these figures. As shown, the particle size distribution of FCA type A is closer to the lower limit, whereas the gradation of natural sand is closer to the upper limit recommended by the Australian Standard. FCA types B and C can be regarded as well-graded fine aggregates.

A sand flow test was conducted in accordance with the NZS 3111 [20] Standard for each type of FCA (A, B, and C) replacing natural sand by 20% increments from 0% to 100%. For the sand flow test, a sufficient amount of sand to obtain a sample of 2500 g after cooling was dried at 110°C to a constant mass; subsequently, it was sieved on 4.75 mm mesh after cooling to the room temperature. The mass of the material retaining on the sieve was measured and recorded as a percentage to the mass of the original sample. This is known as the percentage of oversized material in the sand. A sand mass of that was 0.38 times its dry density was obtained from a material smaller than 4.75 mm. The abovementioned sand was mixed vigorously for 30 s and used for the sand flow test. The dry density of a mixture of natural sand and FCA was calculated using Eq. (1), and the required mixture mass was calculated. This well-mixed mass of sand was placed carefully with the finger over the orifice into a flow cone with a top ring mounted horizontally and centrally above the overflow can with the receiving can. The finger was removed quickly from the orifice, and the stopwatch was started simultaneously. The time required for the sand to be flow out the cone was recorded, and the mass of sand in the receiving pan was



(a) (b) (c)

Fig. 1 Physical appearances of FCAs. (a) Granophyre; (b) basalt; (c) granite.

Table 2 Physical properties of FCAs and natural sand

property	granophyre (A)	basalt (B)	granite (C)	natural sand
apparent particle density (g/cm^3)	2.60	2.93	2.63	2.61
dry particle density (g/cm^3)	2.54	2.56	2.52	2.59
ssd particle density (g/cm^3)	2.56	2.69	2.63	2.60
water absorption	1.0	4.2	0.7	0.3
sand equivalent (%)	58	65	60	98
degradation factor (%)	90	86	88	96
micro fines (%)	6	13	12	3

Fig. 2 Physical appearance of natural sand.

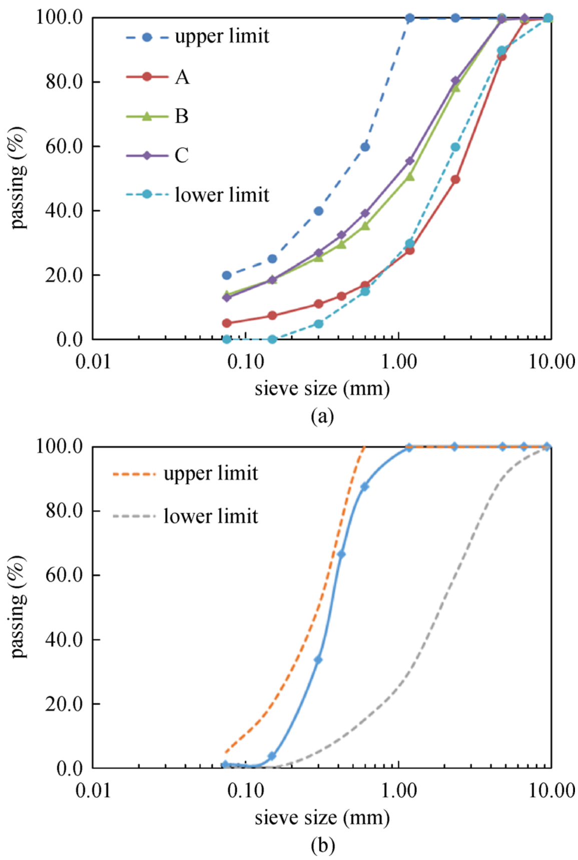


Fig. 3 Particle size distributions of (a) FCAs (A: granophyre, B: basalt, and C: granite); (b) natural sand.

measured. The void content of the sample was calculated using Eq. (2).

$$\gamma_{\mathrm{mix}} = \frac{\gamma_{\mathrm{n}} \times \gamma_{\mathrm{mfs}}}{\gamma_{\mathrm{mfs}}\,(n)\,\% + \gamma_{\mathrm{n}}\,(1-n)\%}, \tag{1}$$

where γ_{mix} is the dry density of the mixture, γ_{n} is the dry density of natural sand, γ_{mfs} is the dry density of the FCAs, n is the percentage of natural sand, and (1–n) is the percentage of FCAs.

$$Void\ content = \left(1 - \frac{1000\,B}{A \cdot D}\right) \times 100, \tag{2}$$

where A is the mass of water (units: g) required to fill the receiving can, B is the mass of sand (units: g) contained in the receiving can as obtained from the average of three runs, and D is the density of dry sand.

2.2 Mixture proportions and concrete test methods

2.2.1 Concrete mixture proportions

Six different concrete mixes were analyzed. The control mix comprised 100% natural sand as the fine aggregate. FCA types A (granophyre) and B (basalt) were used as 40% replacement of natural sand in the mixtures A40 and B40, respectively. FCA type C (granite) was used as 20%, 40%, and 60% replacements of natural sand in mixtures C20, C40, and C60, respectively. The cement content (400 kg/m^3), coarse aggregate size fractions of 20 mm (485 kg/m^3), 14 mm (340 kg/m^3), and 10/7 mm (290 kg/m^3) as well as water content (180 kg/m^3) were maintained constant in all the mixtures. The mix proportions of concretes comprising FCAs and natural sand are shown in Table 3.

2.2.2 Tests of fresh concrete

A workability test of freshly mixed concrete was performed as per AS 1012.3.1 [21]. A conical mold fabricated using steel, with dimensions of 300 mm in height, 100 mm diameter at the top, and 200 mm diameter at the bottom was used to quantify the slump. A bleeding test of concrete was conducted in accordance with the AS 1012.2 [22] Standard. A cylindrical bleeding pot of

Table 3 Mix proportions of concrete

mix	cement (kg/m^3)	coarse aggregate (kg/m^3)	natural sand (kg/m^3)	FCA (kg/m^3)	water (kg/m^3)
control	400	1115	750	0	180
A40	400	1115	450	300	180
B40	400	1115	450	300	180
C40	400	1115	450	300	180
C20	400	1115	600	150	180
C60	400	1115	150	450	180

diameter 250 mm and height 280 mm was used in this experiment. Freshly mixed concrete was placed in the mold in two layers evenly to a level of 5 mm below the top edge. Each layer was compacted using a vibrating table until the surface was free from air bubbles and a smooth concrete surface was achieved. Photographs of the slump and bleeding tests of fresh concrete are shown in Fig. 4.

2.2.3 Tests of hardened concrete

The compressive strength of concrete was determined by testing cylinder specimens of diameter 100 mm and height 200 mm. Testing was performed in accordance with AS 1012.9 [23]. The samples were cured in lime-saturated water for 7 and 28 d before testing. A universal testing machine was used to test the compressive strength. The average compressive strength from three specimens was reported to the nearest 0.5 MPa.

The splitting tensile strength of concrete was determined at 7 and 28 d in accordance with the AS 1012.10 [24] test method. A cylindrical sample of diameter 150 mm and height 300 mm was placed with its axis horizontal on the testing jig and was loaded along the length through a vertical plane at the center in the universal testing machine.

A drying shrinkage test was conducted using the method described in the AS 1012.13 [25] Standard. Test samples of 75 mm × 75 mm × 285 mm prisms with gauge studs fixed at both ends were used to determine the drying shrinkage. All the experiments were conducted using three identical samples, and the mean values are reported in the following sections.

3 Results and discussion

3.1 Effect of FCA on the properties of combined fine aggregates

The ministry of works in New Zealand tested different types of aggregates by the flow cone test method and evaluated their effects on the properties of fresh concrete. Based on the results obtained, an envelope was developed in terms of the flow time and void content, as shown in Fig. 5. This envelop, known as the NZS 3111 [20] flow time limits, can be used to characterize fine aggregates and predict their effect on the properties of mortar and concrete mixtures. Goldsworthy [26] demonstrated the practicability of this test method for evaluating FCAs and their blends with natural sand. It’s been well established that, aggregate shape parameters highly influence the packing density of aggregate [27]. Information from the flow time versus void content of a fine aggregate plotted within the standard envelop was considered suitable for use in concrete and mortar mixtures. Hence, the number of trials to obtain the optimum blend for a specific aggregate can be reduced.

As shown in Fig. 5, the blending of natural sand with 20%, 40%, and 60% FCA types B and C are plotted inside the envelope, whereas those with 80% and 100% FCA types B and C are plotted outside the envelop because they exhibited a flow time of 31 s. All the points are labeled in terms of the FCA type and the percentage replaced for easy identification. For FCA type A, it was discovered that the aggregate did not flow through the cone unless it was sieved on a 2.36 mm mesh. After sieving through a 2.36 mm sieve, the blending of natural sand with 20%, 40%, and 60% FCA type A was plotted inside the envelop, whereas that with 80% FCA type A was plotted on the boundary. Hence, based on the fact that the governing factor for the flow time measurement is the grading, shape, and texture of the fine aggregates, the results suggest that the FCAs are suitable for replacing natural sand by up to 60% for use in concrete and mortar mixtures.

The flow time and void content of the fine aggregates with respect to the percentage of FCA types A, B, and C are plotted in Figs. 6 and 7, respectively. As shown in Fig. 6, the flow time of natural sand for which replacement percentage is zero is the lowest owing to the similar sizes of the particles, the spherical shape, as well as the weathered and smooth texture. FCA type A did not flow through the cone because of the high friction among the particles owing to their angular and flaky shape. Another reason was the presence of oversized particles in FCA type A, which was detrimental to the flow. Generally, the flow

(a) (a)

Fig. 4 Tests to determine fresh concrete properties: (a) slump test; (b) bleeding test.

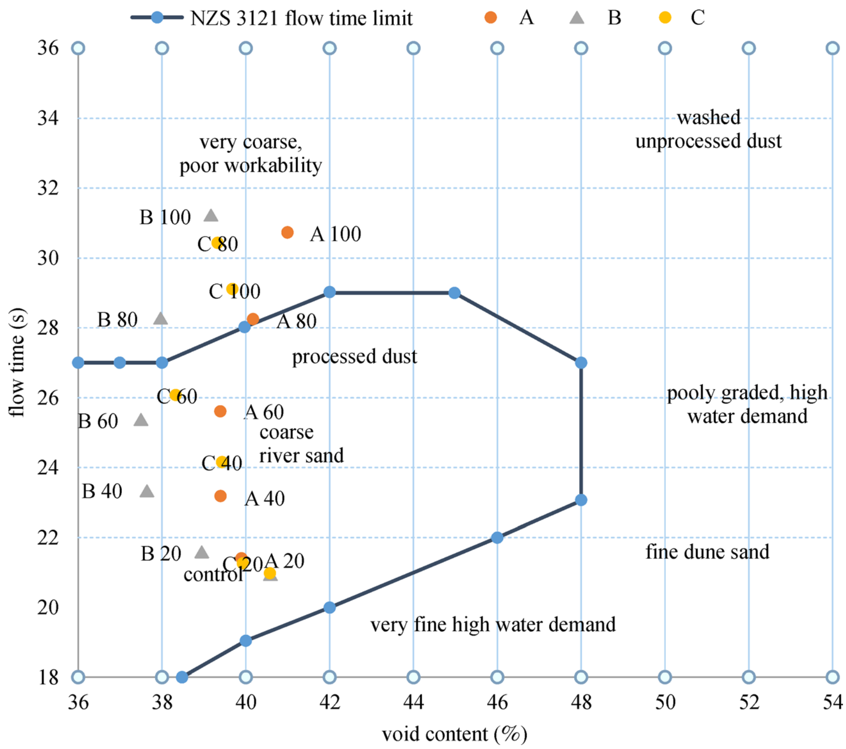


Fig. 5 Flow cone test results.

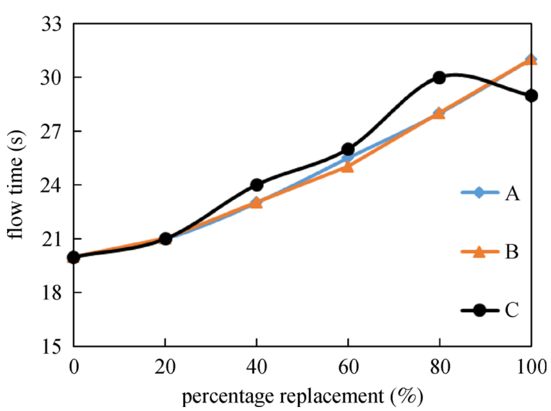


Fig. 6 Variation of flow time with the percentage of FCA.

time increased with the FCA percentage except after 80% replacement of FCA type C. A gradual increment in flow time by approximately 10 s was observed in FCA types A and B with the increase in FCA content from 20% to 100%.

As shown in Fig. 7, the void content decreased gradually with the increase in the FCA content up to 60%. This is attributed to the filling effect of the fine particles present in the FCAs of all three types. With a further increase in the FCA percentage, the void content increased gradually owing to more angular, elongated, and flaky particles contributed by a large fraction of FCAs, which tended to pack loosely. The higher packing density of a particle system will result in a higher flowability at the same water content [25]. FCA type B had the least void content, whereas FCA type A had the highest void content percentage. Conversely, it can be observed from Fig. 8 that FCA type B had the highest packing density, whereas FCA type A had the lowest packing density. According to Marek [9], increasing the amount of fines in FCAs improves the packing density, which is consistent with the findings regarding the FCAs used in this study.

3.2 Fresh concrete properties

3.2.1 Workability

The variation in the workability of fresh concrete was measured in terms of slump. In this study, slumps were compared at 40% sand replacement by FCA types A, B, and C with the control mixture, as shown in Fig. 9. The slump of the control mixture was 140 mm, whereas those of the mixtures with 40% FCAs varied from 120 to 125 mm. Hence, no significant difference in slump values was observed at 40% replacement by FCA types A, B, and C. The replacement of natural sand by 40% FCAs increased the amount of fine particles in the mix as compared with 100% natural sand. Furthermore, the FCA particles were flat, elongated, and rough. These characteristics deteriorated the rheological properties of fresh concrete, as reflected in the reduction of slump from 140 to 120 mm. This result reconfirms that the increase in fines content in

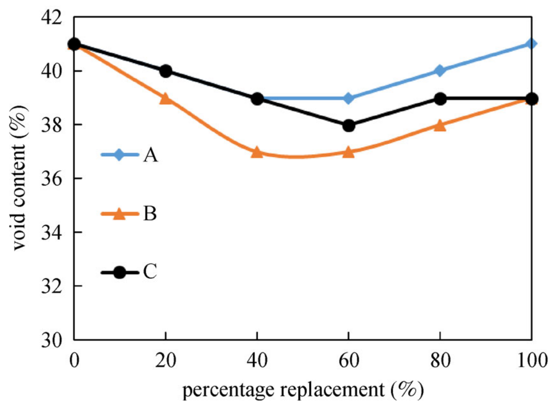


Fig. 7 Variation of void content with the percentage of FCA.

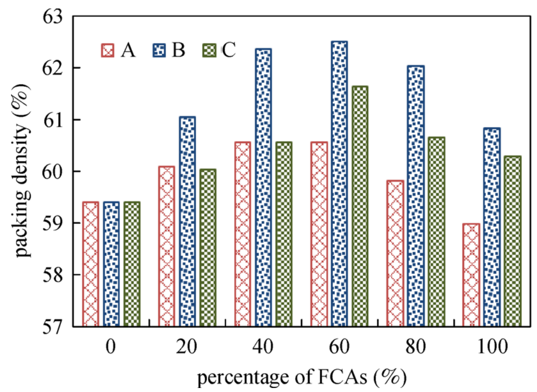


Fig. 8 Variation of packing density with the percentage of FCA.

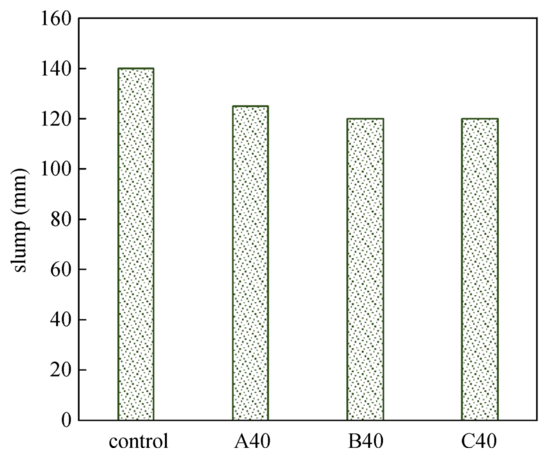


Fig. 9 Slumps of concrete containing 40% FCAs types A, B, and C.

concrete mixtures necessitates additional water to maintain the same workability to wet and minimize the frictional forces generated by the viscosity of paste. Wills [28] studied the effects of the shape characteristics of fine and coarse aggregates on the water demand of concrete and discovered that an equal change in shape characteristics caused fine aggregates to increase the water demand of the mixture by two or three times more than the coarse aggregates. Similar results were also reported by Koehler et al. [29].

Figure 10 shows the variation in slump with the percentage of FCA type C (granite). The results show no noticeable effect on the slump by 20% FCA type C. However, the slump decreased from 140 to 125 mm by 40% FCAs and further to 80 mm by 60% FCAs. Hence, the increase in fine particles and particles with poor shapes and textures significantly affected the workability of fresh concrete, i.e., by FCAs exceeding 20% as sand replacement.

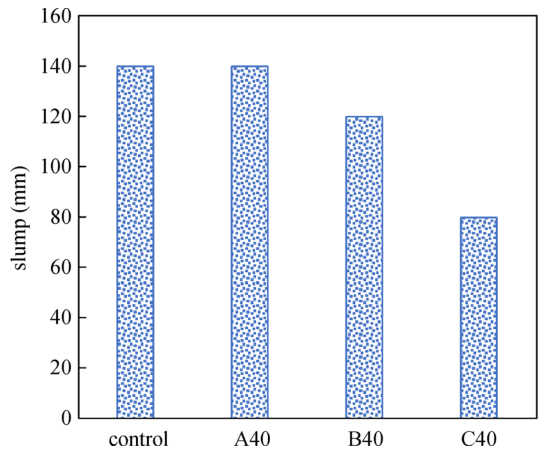


Fig. 10 Variation of slump with the percentage of FCA type C.

The reduction in the slump was more prominent at higher FCA percentages. Cepuritis et al. [30] stated that different aggregate size fractions affected the rheology of fresh concrete because of two known phenomena. The first is the fundamental findings of Krieger and Dougherty [31]: the effect of monosized sphere particles on the flow (viscosity) in a concentrated suspension depends significantly on their normalized solid concentration, i.e., the maximum packing fraction Ψ/Ψ_m (where Ψ is the solid concentration and Ψ_m is the maximum solid concentration or maximum packing). Ψ_m mainly depends on the size distribution and shape of the particles. Therefore, the size distribution and shape of the aggregate particles establish the rheology of concrete. Hence, the use of 60% FCA significantly reduced the workability of concrete owing to the angular shape and higher fines content contributed by FCAs.

3.2.2 Bleeding of concrete

When freshly mixed concrete is placed in a mold and compacted, water rises or bleeds to the surface. Bleeding occurs by water rising in the mixture and the settlement of solid particles. The bleeding rate of the mixes was initially constant and subsequently decreased steadily. The factors affecting the bleeding of concrete included very fine aggregates, admixtures, and temperature, and cement properties [32]. Since the FCAs contained high amounts of fine particles, their effect on concrete bleeding was investigated.

The bleeding test results of concrete using 40% FCA types A, B, and C were compared with that using 100% natural sand, as shown in Fig. 11. The highest bleeding was observed in the concrete with 100% natural sand. As shown, the bleeding decreased significantly due to the use of FCA as 40% replacement of sand. The bleeding values of concrete using 40% FCA were approximately half of that of 100% natural sand. Figure 12 shows that the bleeding of concrete decreased gradually with the increase in FCA content. Zero bleeding was recorded when 60% FCA was used to replace natural sand. The bleeding decreased with the increase in FCAs owing to less free water in the mixture because the high surface area of the FCA fines utilized more water. As the bleeding of concrete decreased significantly with increase in FCAs, their use beyond 40% may pose difficulties in obtaining a smooth finishing after the placing of concrete with a large surface area.

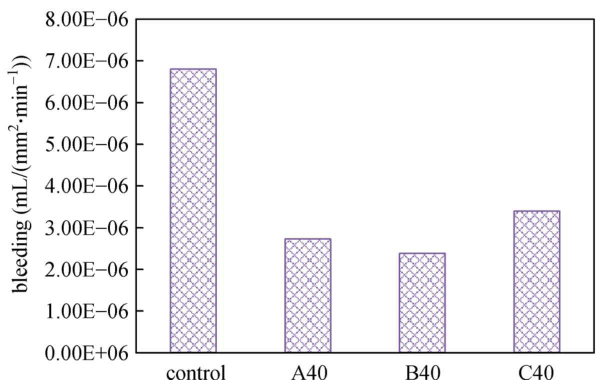


Fig. 11 Bleeding of different concrete mixtures.

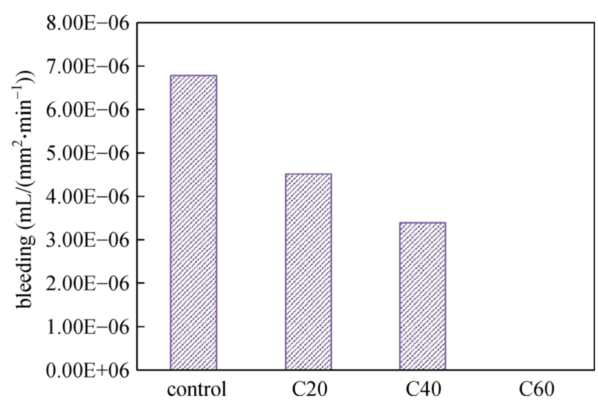


Fig. 12 Variation of bleeding with the percentage of FCA type C.

3.3 Hardened concrete properties

3.3.1 Compressive strength

The comparisons of compressive strengths for different types of FCAs and different percentages of FCA type C are shown in Figs. 13 and 14, respectively. The 28 d compressive strength of the control concrete using 100% natural sand was 46.5 MPa, and those of concretes using 40% FCA types A, B, and C were approximately 50 MPa. Therefore, a slight increase in the 28 d compressive strength was observed when 40% FCA was used. However, no significant difference in compressive strength was observed when 40% FCA types A, B, and C were used. Additionally, the failure patterns of the representative control samples and concrete specimens with 40% FCA type A are shown in Fig. 15. Similar failure patterns were observed in concrete specimens using 100% natural sand and 40% sand replacement by FCAs. The 7 d compressive strengths of the concrete using 40% FCAs were the same as that of the concrete using 100% natural sand, except a slight increase for FCA type B. When the compressive strength development of FCA type C at 28 d was considered, slight increases in strength with the FCA increasing from 0% to 60% were observed, as shown in Fig. 14. A similar trend was observed in the 7 d compressive strengths.

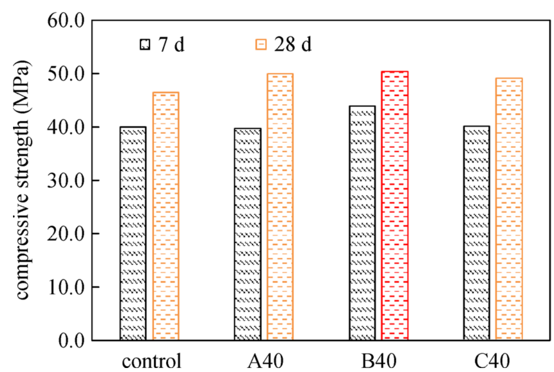


Fig. 13 Compressive strengths of concrete with 40% FCA types A, B, and C.

The small increase in the compressive strength of concrete with the increase in FCAs is attributable to the enhancement in compactness contributed by improved particle packing. The increase in FCAs in the mixture increased the fines content, thereby increasing the compaction of concrete due to the filling of voids by the fine particles of the FCAs. Furthermore, the improved aggregate–binder interface bond by the rough surface of the FCAs was assumed to have contributed to the increase in the compressive strength. Goble and Cohen [33] showed that the surface of fine aggregates can affect the mechanical properties of Portland cement mortar. According to Aitcin

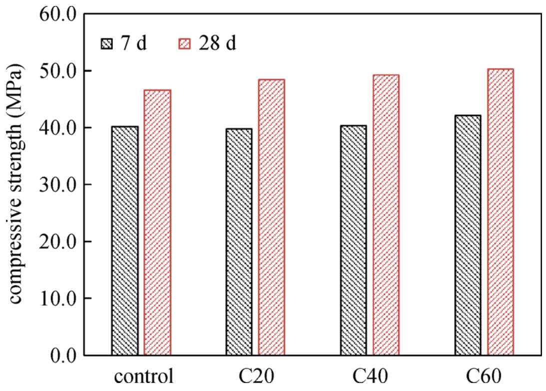


Fig. 14 Variation of compressive strength with the percentage of FCA type C.

Fig. 15 Variation of failure pattern between control samples with FCA concrete.

and Mindess [34], the improvement in the paste-fine aggregates transition zone is attributable to the rough texture of crushed granite fine aggregates, which increases the mechanical interlocking with cement paste. Donza and Cabrera [35] comprehensively investigated the effects of the shape, texture, and mineralogical composition of fine aggregates. Concrete was cast with 25% to 100% crushed sand without dust with a water-to-cement ratio of 0.3, and no significant difference in compressive strength was reported at the ages of 28 and 90 d. Consequently, the authors concluded that the effect of fine aggregates on compressive strength was insignificant when the paste volume remained constant and the crushed sand was dust-free. Hence, the compressive strength results of this study are consistent with the results reported in the literature regarding the effect of similar FCAs.

3.3.2 Splitting tensile strength

The 28 d concrete splitting tensile strength results are shown in Table 4. The maximum split tensile strength of 4.79 MPa was obtained for FCA type A (granophyre) at 40% sand replacement.

This value was slightly higher than the split tensile strength of concrete using 100% natural sand, which was 4.64 MPa. FCA type B showed a splitting tensile strength of 4.44 MPa at 40% replacement of natural sand. FCA type C showed the lowest splitting tensile strength, i.e., 4.09 MPa at 40% replacement of natural sand. This value was slightly lower than that for 100% natural sand. For FCA type C, the split tensile strength decreased with the increase in the FCA percentage. The splitting tensile strength decreased gradually from 4.01 to 3.89 MPa as the FCA percentage increased from 20% to 60%. This marginal tensile strength reduction is attributed to the presence of elongated and flaky particles in the FCAs. Ukpata and Ephraim [36] observed a similar variation in split tensile strength with the increase in quarry dust amount from 25% to 75% in their experiments.

3.3.3 Correlation between split tensile strength and compressive strength

A correlation is typically observed between the split tensile strength and compressive strength of concrete using natural sand as fine aggregates. Hence, empirical equations have been suggest in various concrete design standards to predict the tensile strength of concrete from known values of compressive strength. The ratios of splitting tensile strength to compressive strengths of the mixtures of this study are shown in Table 4. As shown, the ratio of split tensile strength to compressive strength for the control mixture was 0.10, whereas those of the concretes using FCAs as partial replacement of sand varied from 0.08 to 0.10. Hence, it can be concluded that a similar correlation existed between the split tensile strength and compressive strength of concrete using FCAs as partial replacement of sand and that using 100% sand as fine aggregates.

Table 4 Splitting tensile strength of concrete at 28 d

mix ID	compressive strength at 28 d (MPa)	tensile strength at 28 d (MPa)	tensile strength / compressive strength
control	46.5	4.64	0.10
A40	50.0	4.79	0.10
B40	50.3	4.44	0.09
C20	48.3	4.01	0.08
C40	49.2	4.09	0.08
C60	50.2	3.89	0.08

Based on this correlation, simple equations have been suggested in design standards to estimate the split tensile strength as a function of the compressive strength. The splitting tensile strengths of the test specimens were predicted from the compressive strengths using the equations from AS 3600 [37] and ACI 318 [38]. The predicted values of splitting tensile strengths and their comparisons with the experimental values are shown in Table 5. As shown, the ratio of the experimental to estimated split tensile strengths for 100% natural sand was 1.2 for the prediction by AS 3600 [37] and 1.3 for the prediction by ACI 318 [38]. The corresponding ratios for concretes using FCAs were in ranges of 1.0–1.2 and 1.1–1.3 for the predictions by AS 3600 [37] and ACI 318 [38], respectively. Hence, it can be concluded that the split tensile strength of concrete containing FCAs can be predicted by the design standards conservatively and with similar accuracy for concrete using 100% natural sand as fine aggregates.

3.3.4 Drying shrinkage behavior of concrete

The drying shrinkage variations of the concrete specimens with age are shown in Fig. 16. The deformation of concrete was prominent during the early ages, stabilized after 28 d, and increased slightly at 56 d. The concrete specimens with 40% granophyre (type A) and 60% of granite (type C) showed similar behaviors after 21 d. Granophyre at 40% replacement indicated a slightly higher shrinkage than granite at 60% replacement at the initial stage.

The shrinkage of basalt (type B) and granite at 40% replacement indicated similar variations with age. The concrete samples of granite at 20% replacement indicated lower shrinkage values than the concrete using 100% natural sand (control sample). Because the cement content remained constant, the phenomenon above is attributable to the optimum dust content contributed by granite to absorb free water after hydration occurred. According to Tangchirapat and Jaturapitakkul [39], when the sand replacement ratio exceeded a critical level, the drying shrinkage caused by free water evaporation became dominant. Hence, the concrete specimens of mixes C60 and A40 indicated the most significant drying shrinkage. The 56 d drying shrinkage of the mixtures varied in the range of 402–520 microstrain. These shrinkage values were significantly less than the limiting value of 1000 macrostrain recommended by the AS 3600 [37] for general applications.

4 Conclusions

In this study, three types of byproduct FCAs from source rocks of granophyre (A), basalt (B), and granite (C) were used as the partial replacement of sand in concrete. The effects of the FCAs on combined fine aggregate properties were investigated in terms of particle size distribution, flow properties, and void content. Subsequently, the effects of the FCAs on concrete properties were investigated in terms of workability, bleeding, compressive strength, splitting tensile strength, and drying shrinkage. The following conclusions were obtained from the experimental results of this study.

1) Results of the flow cone test demonstrated that the flow time versus void content plots of the combined fine aggregates using up to 60% of all the three FCAs were inside the NZS 3111 [20] envelop, indicating the feasibility of these combinations for use in concrete and mortar mixtures. Generally, the flow time increased with the FCA content. The lowest void contents of the combined fine aggregate were observed for 40% to 60% replacement of natural sand by the FCAs.

2) The use of the FCAs reduced the slump of fresh concrete from 140 mm for no-FCA to 120 mm for 40% FCA. A further increase in FCA type C to 60% reduced the slump significantly to 80 mm. The reduction in workability by the FCAs was attributed to the increased specific surface area by the micro fines and the angularity of the particles.

3) Concrete bleeding decreased by approximately 50% when 40% FCAs were used. A further increase in FCA type C to 60% decreased the bleeding of concrete to zero. The significant reduction in bleeding was primarily attributed to the increase in fines content in the mixture, which increased the demand of free water.

4) The compressive strength increased slightly by the

Table 5 Comparison of experimental and predicted splitting tensile strength of concrete at 28 d

mix ID	split tensile strength at 28 d (MPa)			experimental/calculated	
	experimental	calculated as per AS 3600 [36]	calculated as per ACI 318 [37]	AS 3600 [36]	ACI 318 [37]
control	4.64	3.82	3.44	1.2	1.3
A40	4.79	3.96	3.58	1.2	1.3
B40	4.44	3.97	3.60	1.1	1.2
C20	4.09	3.89	3.51	1.1	1.2
C40	4.01	3.93	3.55	1.0	1.1
C60	3.89	3.97	3.59	1.0	1.1

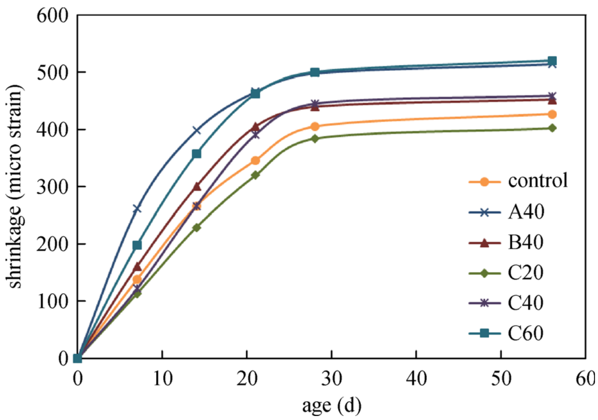


Fig. 16 Variation of drying shrinkage with the age.

use of the FCAs. The FCAs with flow time in the range of 23–25 s and uncompacted void content in the range of 37%–40% yielded concrete with a higher compressive strength than the concrete with 100% natural sand.

5) A marginal reduction in tensile strength was observed for concrete with 40% FCAs as compared with the control concrete. This is attributed to the elongated and flaky particle shape of the FCAs. The splitting tensile strength of concrete comprising the FCAs varied from 8% to 10% of the compressive strength which was similar to that of concrete using 100% natural sand. The empirical equations provided in standards such as AS 3600 [37] and ACI 318 [38] predicted the splitting tensile strengths conservatively with the test-to-predicted strength ratios varying from 1.0 to 1.13.

6) The 56 d drying shrinkage of the mixtures varied in the range of 402–520 microstrains. These values were significantly less than the limiting value of 1000 microstrains recommended by the Australian Standard, AS 3600 [37] for general applications.

7) Therefore, the utilization of these byproduct FCAs can be considered as a sustainable alternative option for the production of high-strength green concrete with acceptable fresh and hardened properties.

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References

1. Saha A K, Sarker P K. Sustainable use of ferronickel slag fine aggregate and fly ash in structural concrete: Mechanical properties and leaching study. Journal of Cleaner Production, 2017, 162: 438–448
2. Roderick Y, McEwan D, Wheatley C, Alonso C. Comparative Study of Building Energy Performance Assessment between LEED, BREEAM and Green Star. West of Scotland Science Park, Glasgow, Kelvin Campus, IES, 2009
3. Saha A K, Sarker P K, Golovanevskiy V. Thermal properties and residual strength after high temperature exposure of cement mortar using ferronickel slag aggregate. Construction & Building Materials, 2019, 199: 601–612
4. Saha A, Sarker P. Mechanical properties of concrete using ferronickel slag as fine aggregate and supplementary cementitious material. Concrete in Australia, 2018, 44(4): 40–44
5. Hudson B. Modification to the fine aggregate angularity test. In: Proceedings of the Seventh Annual International Centre for Aggregates Research Symposium. Austin, TX: Taylor & Francis, 1999
6. Hudson B. Manufactured sand: Destroying some myths. Quarry, 1997, 125: 57–62
7. AS 2758.1. Aggregates and Rock for Engineering Purposes-Concrete Aggregates. Sydney: Standards Australia, 2014
8. Quiroga P N, Ahn N, Fowler D W. Concrete mixtures with high micro fines. ACI Materials Journal, 2006, 103(4): 258–264
9. Marek C. Importance of fine aggregate shape and grading on properties of concrete. In: Proceedings of the Third Annual International Center for Aggregates Research. Austin, TX: University of Texas Library, 1995
10. Çelik T, Marar K. Effects of crushed stone dust on some properties of concrete. Cement and Concrete Research, 1996, 26(7): 1121–1130
11. Li B, Wang J, Zhou M. Effect of limestone fines content in manufactured sand on durability of low-and high-strength concretes. Construction & Building Materials, 2009, 23(8): 2846–2850
12. Kroh T A. Use of manufactured sand as a replacement material for dredged sand in mortar. Dissertation for the Doctoral Degree. Cardiff: Cardiff University, 2010
13. Hameed M S, Sekar A S S. Properties of green concrete containing quarry rock dust and marble sludge powder as fine aggregate. Journal of Engineering and Applied Science, 2009, 4(4): 83–89
14. Ukpata J O, Ephraim M E. Flexural and tensile strength properties of concrete using lateritic sand and quarry dust as fine aggregate. Journal of Engineering and Applied Sciences (Asian Research Publishing Network), 2012, 7(3): 324–331
15. Bahoria B V, Parbat D K, Nagarnaik P B, Waghe U P, Principal Y C C E. Sustainable utilization of Quarry dust and waste plastic fibers as a sand replacement in conventional concrete. In: International Conference on Sustainable Civil Infrastructure. Hyderabad, Telangana: ICSCI, 2014
16. Franklin E K, Vikas S, Agarwal V C, Denis A F, Ehsan A. Stone dust as partial replacement of fine aggregate in concrete. Journal of Academia and Industrial Research, 2014, 3(3): 148–151
17. Singh S K, Srivastava V, Agarwal V C, Kumar R, Mehta P K. An experimental investigation on stone dust as partial replacement of fine aggregate in concrete. Journal of Academia and Industrial Research, 2014, 3(5): 229–232
18. Cheah C B, Lim J S, Ramli M B. The mechanical strength and durability properties of ternary blended cementitious composites containing granite quarry dust (GQD) as natural sand replacement. Construction & Building Materials, 2019, 197: 291–306
19. Gunasekaran K, Praksah Chandar S, Annadurai R, Satyanarayanan K S. Augmentation of mechanical and bond strength of coconut shell concrete using quarry dust. European Journal of Environmental and Civil Engineering, 2017, 21(5): 629–640

20. NZS 3111. Method for Determining Voids Content, Flow Time and Percentage over Size Material in Sand. Wellington: Standards New Zealand, 1989
21. AS 1012.3.1. Methods of Testing Concrete Determination of Properties Related to the Consistency of Concrete—Slump Test. Sydney: Standard Australia, 2014
22. AS 1012.2. Methods of Testing Concrete Method 2: Preparing Concrete Mixes in the Laboratory. Sydney: Standard Australia, 2014
23. AS 1012.9. Methods of Testing Concrete—Determination of the Compressive Strength of Concrete Specimens. Sydney: Standard Australia, 1999
24. AS 1012.10. Methods of Testing Concrete—Determination of Indirect Tensile Strength of Concrete Cylinders. Sydney: Standard Australia, 2000
25. AS 1012.13. Methods of Testing Concrete—Determination of the Drying Shrinkage of Concrete for Samples Prepared in the Field or in the Laboratory. Sydney: Standard Australia, 2000
26. Goldsworthy S. Manufactured sands in Portland cement concrete. In: Proceedings of the Third Annual International Center for Aggregates Research. Austin, TX: University of Texas Library, 2005
27. Kwan A, Mora C. Effects of various, shape parameters on packing of aggregate particles. Magazine of Concrete Research, 2001, 53(2): 91–100
28. Wills M H. How aggregate particle shape influences concrete mixing water requirement and strength. Journal of Materials, 1967, 2(4): 843–865
29. Koehler E, Jeknavorian A, Chun B, Zhou P. Ensuring Concrete Performance for Various Aggregates. In: The 17th Annual ICAR Symposium. Austin, TX: Resurchify, 2009
30. Cepuritis R, Jacobsen S, Pedersen B, Mørtsell E. Crushed sand in concrete—Effect of particle shape in different fractions and filler properties on rheology. Cement and Concrete Composites, 2016, 71: 26–41
31. Krieger I M, Dougherty T J. A mechanism for non-Newtonian flow in suspensions of rigid spheres. Transactions of the Society of Rheology, 1959, 3(1): 137–152
32. Neville A M. Properties of Concrete. 4th ed. New York: Wiley, 1995
33. Goble C F, Cohen M D. Influence of aggregate surface area on mechanical properties of mortar. ACI Materials Journal, 1999, 96(6): 657–662
34. Aitcin P, Mindess S. High-performance concrete: Science and applications. Capitulo, 1998, 10: 477–512
35. Donza H, Cabrera O. The influence of kinds of fine aggregate on mechanical properties of high strength concrete. In: The Fourth International Symposium on Utilization of High-Strength/High-Performance Concrete. Paris: British Library Conference Proceedings, 1996
36. Ukpata J O, Ephraim M E. Flexural and tensile strength properties of concrete using lateritic sand and quarry dust as fine aggregate. Journal of Engineering and Applied Sciences (Asian Research Publishing Network), 2012, 7(3): 324–331
37. AS 3600. Concrete structures. Sydney: Standard Australia, 2009
38. ACI 318. Building Code Requirements For Structural Concrete. Michigan: American concrete institute, 1999
39. Tangchirapat W, Jaturapitakkul C. Strength, drying shrinkage, and water permeability of concrete incorporating ground palm oil fuel ash. Cement and Concrete Composites, 2010, 32(10): 767–774