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Engineering properties of concrete made with GGBS and pulverised fuel ash

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الخصائص الهندسية للخرسانة المصنوعة باستخدام خبث الأفران الحبيبي المطحون والرماد المتطاير

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Abstract:
The utilisation of supplementary cementitious byproducts, including ground granulated blast-furnace slag (GGBS) and pulverised fuel ash (PFA) as a part of cement in concrete technology, has received great attention in recent years. This paper delineates the influence of using GGBS and PFA as a cement substitute on the physico-mechanical characteristics of concrete. To do so, different concrete formulations were compositionally blended at water to cement ratio of 0.5, and a fixed blending proportion of 1 cement: 2 sands: 3 aggregates. Subsequently, multi-scale analyses entailing the slump, density, compressive strength, tensile strength test were performed to assess their performance. Correspondingly, the results revealed an increase in consistency as a result of incorporating GGBS or PFA as a 60% cement substitution, especially for concrete formulation rich in GGBS. As for the strength observations, it was indicated that using GGBS and PFA induced a reduced UCS, particularly in at earlier curing age, but such a decrease was compensated at longer curing period. As for the TSS performance, the results showed that GGBS-based concrete yielded a superior TSS at 28 days, while PFA induced a gradual TSS reduction as the PFA content increased. These promising outcomes suggest the possibility of developing sustainable concrete by incorporating high amount of GGBS and PFA, providing an attractive way for preserving the environment from the impact of cement manufacturing.

Keywords: Supplementary materials, pozzolans, workability, compressive and tensile strength.

الملخص
حظي استخدام المواد التكميلية او المضافة بما في ذلك خبث الافران العالي الحبيبية ومسحوق الرماد المتطاير كجزء من الاسمنت في تكنولوجيا الخرسانة باهتمام كبير في السنوات الاخيرة، يوضح هدا البحث تأثير كل من خبث الافران العالي الحبيبية ومسحوق الرماد المتطاير كجزء من الاسمنت على خصائص الخرسانة الطازجة والمتصلبة. وللقيام بدالك، تم تصميم مجموعة من الخلطات الخرسانية باستخدام نسبة ماء الى مثبت (0.5) ونسبة مثبت (1) الى رمل (2) الى ركام (3). بعد دالك، قد تم اجراء تحليل متعدد المقاييس بما في دالك اختبار الركود، اختبار الكثافة، اختبار قوة الضغط واختبار قوة الشد لتقييم اداءها. في المقابل، كشفت النتائج عن زيادة في مقدار الركود بسبب استخدام كل من خبث الافران العالي الحبيبية ومسحوق الرماد المتطاير كجزء كبير (60%) من الاسمنت، لاسيما في حالة خبث الافران العالي الحبيبية. وأشارت مقاومة الضغط الى انه: بالرغم من تعويض النقص في المقاومة على مدى فترة المعالجة المطولة، فان استخدام خبث الافران ومسحوق الرماد المتطاير كجزء من الاسمنت يؤدي الى انخفاض في قوة الضغط بالأخص في فترة المعالجة المبكرة وفي

حالة استخدام مسحوق الرماد المتطاير. اما بالنسبة لمقاومة الشد، فقد أظهرت النتائج بان استخدام خبث الافران قد تسبب في زيادة قوة الشد بينما استخدام مسحوق الرماد المتطاير قد تسبب في تقليل متدرج في مقاومة الشد. تشير هده النتائج الواعدة الى إمكانية تطوير خرسانة صديقة للبيئة وتحتوي على كمية كبيرة من خبث الافران العالي الحبيبية ومسحوق الرماد المتطاير مما يوفر طريقة واعدة للحفاظ على البيئة من التأثير السلبي لتصنيع الاسمنت.

الكلمات المفتاحية: المواد المضافة او التكميلية، البوزولان، التشغيلية، مقاومة الضغط والشد.

Introduction

The construction sector is one of the intensive structural material consumers, accountable for approximately 24% of the total raw material consumptions [1]. Concrete continues to perform a dominating role ahead of steel, plastic, and wood in the construction industry [2]. This is due to its cost efficiency and its application versatility [3]. Concrete is also rated as the second most utilised material globally, behind water [4,5], with about 10 billion tonnes of concrete produced annually, and such a number is anticipated to raise to about 18 million tonnes by 2050 worldwide [1]. However, the production of cement, which is estimated to be 500 million tonnes globally by 2050 [6], is an un-environmentally unfriendly binder. This is because of its significant demand for raw materials (2.8 tonnes per Portland cement tonne) [7], its intensive energy consumption during manufacturing (5000 MJ per tonne) [8], and the considerable greenhouse gas emissions (tonne of CO_2 per tonne of cement) associated with its manufacturing [1], which stands for about 5 % of the carbon dioxide emissions in the world [9]. This considerable greenhouse gas emission is approximately divided into three categories: mainly 50% because of the calcination of limestone, 40% because of the fuel ignition process in the kiln, and 10% due to the cement production and conveyance [1]. Thereby, the industrial production process for the cement is among the significant contributors to universal warming. In addition, the design of concrete by using Portland cement as an independent binder also can cause a problematic issue such as ettringite nucleation [10], which has high water absorption capability [11–15], thus leading to a deteriorative phenomenon such as crack formation, concrete expansion, and even concrete destruction. Therefore, there is an urgent need for exploring and adopting more economical and eco-friendlier, effective, and feasible alternative solutions for Portland cement [16].

One of the effective solutions for cement environmental concerns is the incorporation of manufacturing by-products (pozzolans) including GGBS, and pulverised fly ash-PFA [17]. The GGBS and PFA, which are a pozzolanic materials rich in aluminosilicate compounds produced through steel manufacturing and electricity power stations [18], respectively, are annually produced with about 530 million and one billion tonnes globally [1], of which only 65% and 25% being used [19]. Disposal of these by-products has, recently, become costly, occupying a large area of land, and causing serious environmental issues [19]. Particularly, PFA, as it is contaminated material containing leachable toxic trace elements, which condense from the flue gas [20], and can cause serious ecological problems to both soil and water [1]. Therefore, the re-utilisation of such by-products in concrete has been encouraged, due to their potential in improving the physical (workability) and mechanical (compressive and tensile strength) characteristics of concrete owing to their high pozzolanicity and their filler effectiveness [21]. In addition, these pozzolans are by-products; hence, their usage as a cement substitution could serve as a promising sustainable solution of disposal, contributing to sustainable concrete construction.

In the literature, [10] as an instance, substituted 0, 25, 50, and 75% of Portland cement with GGBS, and investigated such substitution levels on the durability performance of concrete. The observation of such a study indicated that cement substitution with 50% GGBS experienced the optimal performance in the presence of sodium sulfate under moist curing, while 75% substitution level was superior in the case of steam condition. Bahratkumar, Raghuprasad, Ramachandramurthy, Narayanan, and Gopalakrishnan [22] established a decline in the fracture energy owing to the inclusion of both GGBS and PFA as part (50% and 25%, respectively) of cement. Hadisadok, Kenai, Courard, Michel, and Khatib [23] examined the effect of a separate 5% sodium sulfate and 5% magnesium sulfate on concrete and suggested the use of more than 30% of low reactivity GGBS as a partial cement replacement for better sulfate resistance. Siddique and Bennacer [24] reported that the optimum cement replacement ratio with GGBS varies from 25% to 89%, depending on the oxide compositions and glass content of GGBS and the fineness of both Portland cement and GGBS.

Accordingly, it is obvious that the utilisation PFA and GGBS as a cement substitution can be possible and beneficial, but there is a discrepancy between researchers. Therefore, as part of this research stream, this study aimed at unveiling the possible synergetic impact of co-incorporating GGBS and PFA as a high replacement (60%) of Portland cement to obtain an eco-friendly, sustainable concrete.

Methodology

Materials

Three different cementitious materials, two grades of coarse aggregates, one type of sand and deionised water, were employed in the laboratory experiments. The cementitious materials entailed; 1) Portland cement (PC) having a physical texture of a grey powder, GGBS in the physical form of off-white powder, and pulverised fuel ash (PFA) in the physical form of light grey powder. The PC used was a type of CEM-II Portland cement, confirming the specification of [25], and was acquired from Large Cement UK. The GGBS utilised was in compliance with [26], and was resourced from Civil and Marine Cement Ltd, LIanwern, UK. The PFA used, which is produced in a power station, was in adherence with BS EN 450-1: 2012 [27], and was sourced by a local supplier. The oxide compositions of all the cementitious materials are listed in Table 1, whereas their physical properties are listed in Table 2.

Table 1 Oxides of cement and GGBS.

Oxides	Cement	GGBS	PFA
CaO	63	37.99	0.22
MgO	4.2	8.78	0.43
SiO_2	20	35.54	59.04
Al_2O_3	6	11.46	34.08
Na_2O	0.02	0.37	1.26
P_2O_5	0.1	0.02	-
Fe_2O_3	3	0.42	2.00
Mn_2O_3	0.06	0.43	-
K_2O	0.57	0.43	-
SO_3	2.3	1.54	0.05
Loss on ignition	0.8	2	0.63

Table 2 Physical characterises of cementitious materials.

Characteristics	PC	GGBS	PFA
Insoluble residue	0.49	0.29	0.4
Density (kg/m^3)	1390	1190	900
Relative density (Mg/m^3)	2.9	3	2.3
Glass amount	-	98	-
Fineness	370	440	600
pH value	13.38	10	-
Glass content	-	91	79
Colour	Grey	White	Grey
Form	Powder	Powder	Powder

The coarse aggregates used were two natural crushed limestone aggregates (CA); one with a particle size ranging from 20 to 10 mm (grade 20) and one with a size ranging from 10 mm to 4 mm (grade 10), while the fine aggregate was a natural river sand from Bristol channel. Both aggregates were compliant with BS EN 12620:2002+A1 [28] and were obtained from a local quarry through a local supplier. Some characteristics of the aggregates are shown in Table 3, while the particle size distribution of 20 mm-CA and 10 mm-CA and FA, which were obtained using dry sieve analysis, are plotted in Figure 1.

Table 3 The physical characteristics of aggregate used in this research

Physical characteristics	CA		FA
	20 mm	10 mm	
Cu	1.3	3.2	0.1
Cc	7.4	1.49	1.76
Flakiness index	22	33	-
Elongation index	11.9	20	-
Shape index	6.9	11.9	-
Impact value	14.9	22.9	-
Particle density	-	2.7	2.59
Water absorption	1.09	1.9	20

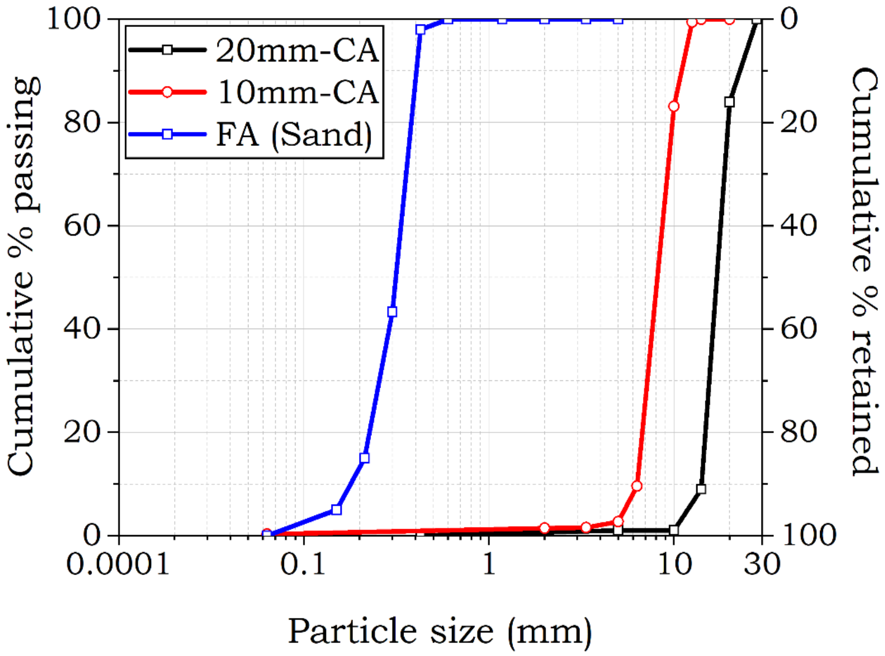

Figure 1: Particle size distribution of raw materials.

Mix compositions and specimens manufacturing.

Four unique concrete formulations (see Table 4, including 1) one control concrete batch (100% PC, used as a benchmark); 2) one concrete batch with 60% GGBS as a cement mass replacement (40%PC-60%GGBS); 3) one concrete batch with 60% PFA as a cement mass replacement, and one concrete batch with ternary blend of 40% PC, 30% GGBS and 30% PFA, were prepared under a laboratory condition. For all the concrete batches, the water/binder (w/b) ratio was fixed at 0.5. In addition, the mix code was fixed compositionally at a binder: sand: 20mm-CA: 10mm-CA proportion of 1:2:1:2. The purpose was to examine the possible impact of both GGBS and PFA on the physico-mechanical characteristics of concrete, and to produce a sustainable concrete mix containing high amount of pozzolans.

Table 4 Binder compositions proportions of concrete formulations.

Concrete mix code	Binder proportion (kg)		
	Cement	GGBS	PFA
M1 (100PC)	6	-	-
M2(60GGBS)	2.4	3.6	-
M3(30GGBS-30PFA)	2.4	1.8	1.8
M4(60PFA)	2.4	-	3.6

A total of nine cubical concrete specimens measuring 10 cm in width and 10 cm in height, and three cylindrical samples (100 mm in diameter and 200 mm in height) were produced under a laboratory condition in adherence with the specification outlined in [29], [30], and [31]. For each concrete formulation, enough quantity of the solid constituents (PC, GGBS, PFA, 20mm-CA, 10mm-CA and FA) were firstly blended in a mechanical mixer for 3 minutes, before the moisture content was gradually added and the rotation sustained for an additional 3 min. Subsequently, the workability of fresh mixture was established by means of the slump test, conducted in line with [32]. The fresh concrete was then placed into the pre-lubricated cubical/cylindrical steal moulds and quivered by means of vibrating table for 1 min to decrease the amount of air voids within the concrete cubes. Subsequently, the casted concrete cubes were stored under room environment at a temperature of 20±5 °C. At the end of 24 h, the hardened samples were demolded and placed in a fabricated tank filled with water at a 20±5 °C, readying for latter testing.

Testing method

The performance of produced concrete cubes was assessed through the consistency (fresh property) and the mechanical characteristics (hardened property). The consistency was assessed by means of the slump test, in adherence with [32]. The mechanical properties were evaluated through a several testing entailing the density, UCS, and TSS. The density test was performed in line with [33], on three cubical concrete specimens per mix composition at 28 days of moist curing. The UCS test was performed in line with [34], on three concrete samples at the ending of 7, 14 and 28 days of curing. As for the TSS test, it was conducted in adherence with [35] by using three cylindrical concrete specimens for each concrete mix after 28 days of curing.

Results and discussion

Concrete workability

The workability results, measured using the slump test, for concrete made with binary and ternary blended binders of PC, GGBS and PFA, are presented in Figure 2, along with the slump value of PC-based counterpart for a comparison. As expected, the slump result indicated that the incorporation of GGBS or PFA alone or in blend as a 60% cement replacement induced a variation in the slump.

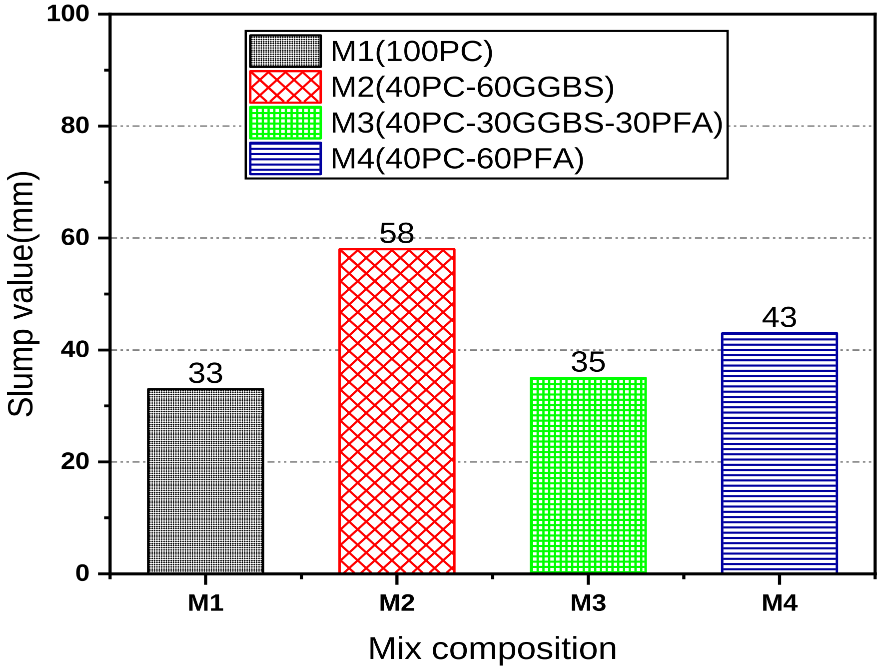

Figure 2: Consistency of fresh concrete measured using the slump test.

As seen in Figure 2, M2 (40PC-60%GGBS) exhibited the highest slump value of 58 mm, thus suggesting the reduction of water demand. This slump improvement, which was in line with several research studies [36–39], is probably due to the smoothness of the surface morphology of the GGBS, the lower water absorption ability of GGBS, the higher specific gravity of the GGBS, the poorer hydration interaction of GGBS-based concrete, and the dense surface appearance of the GGBS, which produce slip planes. The lower calcium oxide of GGBS-based concrete is also a contributing factor, as it induces a reduction in heat hydration and delays the setting/hardening of the concrete. All these factors facilitate particle movement, thus inducing an improved consistency.

On the complete substitution of GGBS with PFA, however, the improvement in the concrete consistency was slightly diminished, where M4 exhibited a slightly lower slump of 43 mm as compared to that of 58 mm for the GGBS-based counterpart, although such a slump was higher than that of 33 mm for M1-100PC. Accordingly, this proposes not only the dominance of GGBS on the expense of PFA independently (M4-40PC-60PFA) as a 60% partial cement substitution, but also the beneficial impact of PFA in improving the concrete workability. The enhanced consistency induced by PFA relative to the control mix, which was in an agreement with several studies [19,40–43], is possibly due to the spherical morphology, the smooth glassy texture, and the lower surface area of the PFA, all of which minimizes or revokes the friction of the aggregates-pastes and acts as miniature ball bearing, providing a lubricant effect within the concrete system.

As for the ternary blended binder of 40PC-30GGBS-30PFA as given by M3, the result revealed a negligible consistency improvement, as part (60% on a mass basis) of cement was substituted with an equal combination of GGBS and PFA, where only a 2 mm increase in the slump, relative to the control mix, was recorded. Accordingly, this implies the restriction of the advantageous impact of both GGBS and PFA on the workability, which is possibly attributed to the change in the size distribution and the oxide compositions of the ingredients within the system, of which the latter induces a higher heat hydration, thus the acceleration of water consumption, thereby leading to poorer workability. Therefore, it can be finally concluded that the use of GGBS or PFA as a part of cement on a mass basis induces an improved consistency, and such an improvement is more pronounced in the case of using GGBS independently.

Hardened Density

Figure 3 displays the variation in the density of the concretes at a moist curing age of up to 56 days. In general, all the concrete cubes revealed an increase in the density as the curing period increases, indicating the continuous formation of hydrated products, which in turn densify the host concrete matrix.

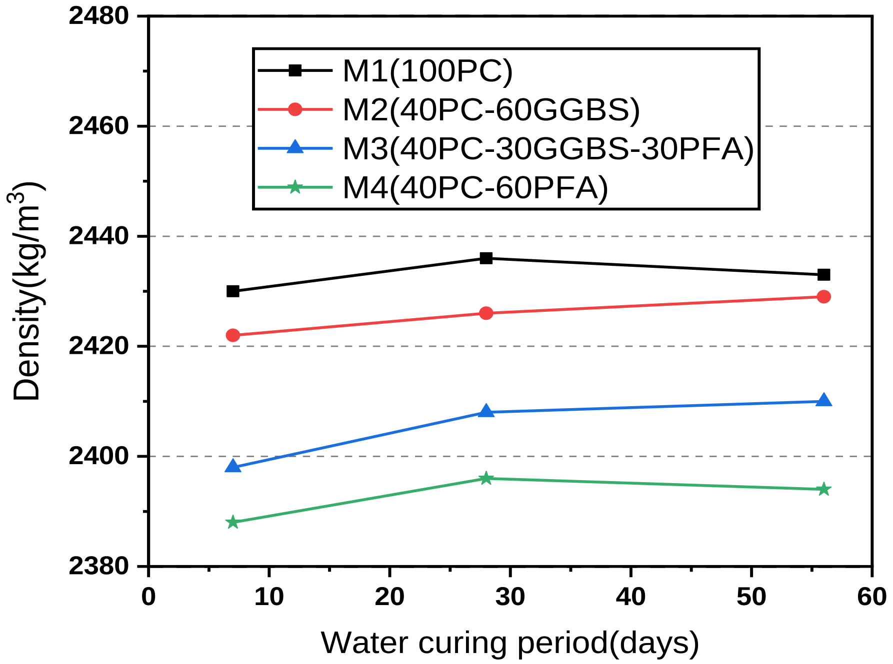

Figure 3: Density trend of concrete cubes over a curing period of 56 days.

As seen in Figure 3, the control mix (M1), in which no cement replacement was applied, experienced the highest density at all the prescribed moist curing periods, indicating a higher degree of densification due to the formation of hydrated products. However, by substituting 60 % of PC with GGBS and PFA on their own or in combination as given by M2 (40PC-60GGBS), M4 (40PC-60PFA) and M3 (40PC-30GGBS-30PFA), the result revealed a density decrease ranging from 10 kg/m^3 to 40 kg/m^3 at the curing age of up to 28 days, and such a decrease was slightly compensated at the curing age of 56 days. This reduction in density, however, was more obvious in concrete samples containing a higher quantity of PFA, suggesting the significant influence of PFA on the density of concrete. The decline in density due to the inclusion of GGBS and PFA was also reported in several studies [43–49]. The logical rationale behind this density reduction trend can be assigned to the increase in voids associated with PFA and the sequence order of the specific gravity of the binder, where such a sequence (from high to low) in the concrete density (M1>M2>M3>M4) was in accord with the specific gravity domination of the binder (PC>GGBS>GGBS-PFA>PFA).

Compressive strength (UCS).

The UCS evolution for all the concrete cubes cured in water for a period of up to 56 days is shown in Figure 4. In this perspective, the UCS observation revealed gradual UCS development with the increase in curing period for all the concrete formulations, suggesting a continuous nucleation and growth of hydrated products that play a positively significant role in the strengthening of the concrete matrix. The display of UCS development of ordinary concrete is commonly ascribed to the formation of new hydrates due to the hydration of cement in the presence of water, and such hydrates included CSH and CAH, among others, all of which densifying and interlocking the concrete matrix, thereby increasing the concrete's capability in resisting loads.

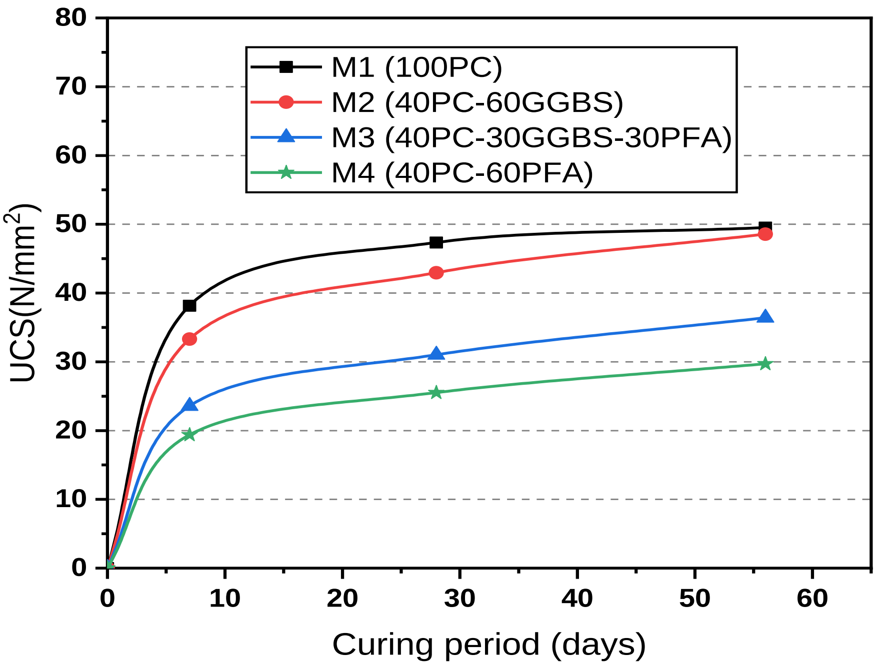

Figure 4: Unconfined compressive strength (UCS) of concretes made with GGBS and PFA.

Like the case of density performance, the benchmark concrete (M1 100PC) tended to show the highest UCS at all the prescribed curing periods, achieving a UCS value of 50 N/mm^2 at 56 days of curing, of which only 3 N/mm^2 was gained after 28 days. This implies that the strength progress mostly occurs through the early 28-day curing period, which is in consistence with the common typical strength growing trend. The superiority of conventional concrete is perhaps owing to the degree of tricalcium silicate in the Portland cement, which is in charge of the earlier age gain because of the nucleation and growth of the CSH gel that interlocks the concrete system.

The presence of GGBS as given by M2 (40PC-60GGBS) indicated a decline in the UCS at the initial curing age, where M2 yielded an UCS of 33 and 43 N/mm^2 at 7 and 28 days, relative to that of 38 and 47 N/mm^2 for the control concrete (M1), respectively. This reduction in strength, however, seems to be compensated for at a prolonged period, where M2 yielded a 56-day UCS of 49 N/mm^2, compared to 50 N/mm^2 for the control concrete (M1). This trend, therefore, implies the continued pozzolanic reactions, which is also an indication of the possible domination of GGBS-based concrete over the conventional concrete if a further curing period is provided. This reduction trend was also in agreement with the consensus among engineering researchers [36]. The strength reduction behind the inclusion of GGBS at an early age (7 and 28 days) can be attributed to the lower calcium oxide, the slow hydration reactivity of GGBS and the delay of hydration reaction, resulting in the retardation of the hardening of GGBS-based concrete, as compared to control concrete [50]. The strength improvement compensated at the prolonged age of 56 days is possibly because of the higher amount of silicon and alumina oxide produced from the participation of GGBS. Such produced oxides facilitate the nucleation of extra hydrates (pozzolanic compounds), which induce pore-blockage, thereby densifying the system, and inducing denser microstructure, all of which induces an improved strength [19,50].

On the substation of GGBS with PFA, the UCS trend exhibited a further gradual strength reduction as the GGBS substitution level increases, accounting for a 56-day UCS of 36 N/mm^2 for M3 (40PC-30GGBS-30PFA) and 30 N/mm^2 for M4 (40PC-60PFA). This trend suggests the superiority of GGBS-rich binder in the development of higher UCS over that of PFA-based binders. Zhu, Yang, and Yao [51] also reported a continuous reduction in the UCS as the GGBS/PFA ratio decreases in concrete made with a 70% cement replacement. The lower UCS value induced using PFA can be credited to the relatively lower reactiveness and lower CaO amount (0.22%) of PFA in relation with to both cement (63%) and GGBS (40%) [19]. As the PFA quantity rises, as the CaO declines, resulting in poorer hydration kinetics, thereby postponing the development of the hydrates that are in charge of the interlocking of the concrete system.

Tensile splitting strength (TSS)

The TSS is an important engineering aspect, as it indicates the concrete behaviour to crack development and shear failure. Figure 3 represents the TSS of concrete containing GGBS and PFA at 28 days of ambient curing, along with the conventional control concrete as a reference. Unlike the UCS, the result showed that the incorporation of GGBS as a 60% PC substitution experienced an increase in the TSS as given by M2, where the TSS was increased from 4.3 N/mm^2 for the control concrete to 4.5 N/mm^2 for M2 (40PC-60GGBS). This, however, was not the case of GGBS-PFA-based and PFA-based concretes, where the TSS was reduced to 3.6 N/mm^2 and further reduced to 2.5 N/mm^2, as illustrated by M3 (40PC-30GGBS-30PFA) and M4 (40PC-60PFA), respectively. The superior performance of GGBS in enhancing the TSS is probably owing to the creation of more hydrates via the pozzolanic interaction of GGBS which facilitates the densification of concrete matrix and the reduction of voids [52], all of which improves the Xu, Tian, Miao, and Liu [53] also reported a similar TSS trend and attributes the TSS increase induced by GGBS to the morphology of the hydrated products, where the morphology of the hydrates produced in PC-GGBS-based concrete, under the scanning electron microscopy, looks like interweaving thick needles, as opposite to that of PFA-based concrete which seems to be villous. Berndt [54] also reported a gradual reduction in the TSS as the quantity of PFA increases, due to the poorer interfacial bond between the Portland cement gel and the aggregate [46,47].

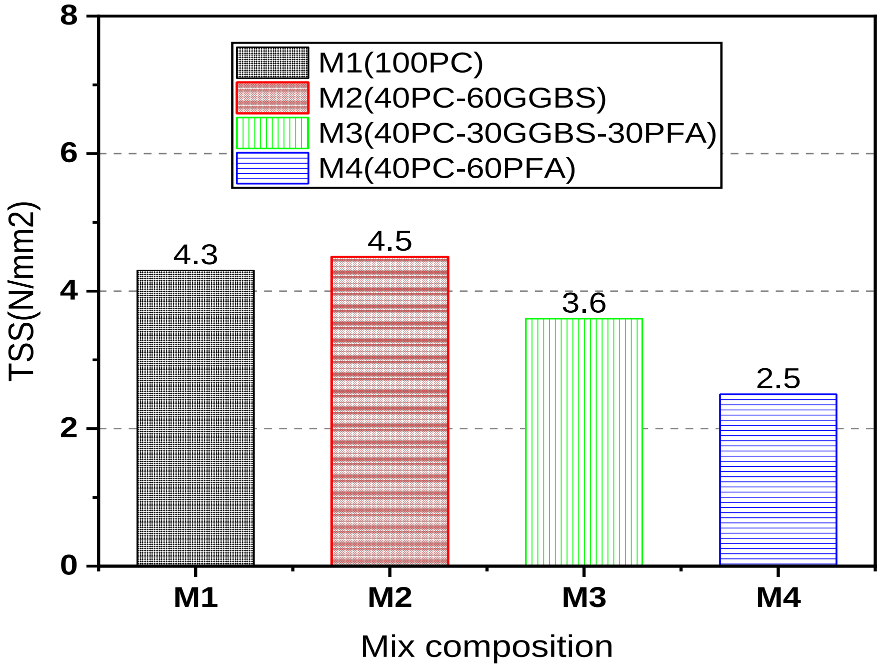

Fig 5: Tensile splitting strength (TSS) of concretes made with PC, GGBS and PFA.

Conclusion

The outcomes of the laboratory experiment suggested the possibility of developing a sustainable concrete using a binary mixture of GGBS and PFA as a high substitution percentage (60%) of Portland cement. Therefore, the main observations are listed accordingly:

1-Using GGBS as a part (60%) of PC facilitates particle movement due to its smooth surface morphology, its proper early hydration reaction, and its lower water absorption capability.

2-Incorporating PFA separately as a partial (60%) cement substitution increases the workability of concrete because of its spherical morphology, its smooth glassy texture, and its lower specific surface area.

3-The co-addition of GGBS and PFA as a high (60%) cement substitution exhibited a lower consistency relative to their individual usages, although such a consistency is still better than the conventional concrete. This is owing to the change in the particle texture and the oxide compositions of the system.

4-The inclusion of GGBS and PFA on their own or in combination, as a part of cement, decreases the density and the UCS, and such a decrease was more obvious at the initial curing stage and in the case of PFA alone. This is because of the lower particle density of GGBS and PFA, the reduction in tricalcium silicate content of the binder, the lower reactivity of PFA, the slow GGBS hydration reactivity and the lower CaO amount of PFA.

5-The utilisation of GGBS as a 60% substitution of cement induced a higher TSS, while the presence of PFA alone or in combination with GGBS experienced a reduction in TSS. This can be credited to the morphology of the hydrates produced by GGBS and PFA, where the hydrates in the former seem to be in the form of interweaving thick needles, whereas in the latter seem to be villous, inducing a poorer bond between the PC gel and aggregate.

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