International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:13, No:9, 2019

Sustainable Development of Medium Strength Concrete Using Polypropylene as Aggregate Replacement

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Abstract**—**Plastic as an environmental burden is a well-rehearsed topic in the research area. This is due to its global demand and destructive impacts on the environment, which has been a significant concern to the governments. Typically, the use of plastic in the construction industry is seen across low-density, non-structural applications due to its diverse range of benefits including high strength-to-weight ratios, manipulability and durability. It can be said that with the level of plastic consumption experienced in the construction industry, an ongoing responsibility is shown for this sector to continually innovate alternatives for application of recycled plastic waste such as using plastic made replacement from polyethylene, polystyrene, polyvinyl and polypropylene in the concrete mix design. In this study, the impact of partially replaced fine aggregate with polypropylene in the concrete mix design was investigated to evaluate the concrete's compressive strength by conducting an experimental work which comprises of six concrete mix batches with polypropylene replacements ranging from 0.5 to 3.0%. The results demonstrated a typical decline in the compressive strength with the addition of plastic aggregate, despite this reduction generally mitigated as the level of plastic in the concrete mix increased. Furthermore, two of the six plastic-containing concrete mixes tested in the current study exceeded the ST5 standardised prescribed concrete mix compressive strength requirement at 28-days containing 1.50% and 2.50% plastic aggregates, which demonstrated the potential for use of recycled polypropylene in structural applications, as a partial by mass, fine aggregate replacement in the concrete mix.

Keywords**—**Compressive strength, concrete, polypropylene, sustainability.

I. Introduction

PLASTIC is a polymer based material which due to its durability, strength to weight ratio, corrosion resistance and versatility can be used in a wide range of applications and it has several benefits in sustainability. However, this material due to its characteristics has few drawbacks e.g. high embodied energy, low modulus of elasticity and high thermal expansion which require further detailing to be utilised in construction.

In terms of sustainability, plastic materials are recyclable which makes them more flexible to the requirements and the production of plastic materials consumes less water. Moreover, the environmental cost to utilise alternative materials over plastic would be nearly 4 times greater due to the plastic's greater efficiency [1].

In the construction industry, it can be said that with the level of experienced plastic consumption, an ongoing responsibility is shown for this sector to continually innovate alternatives for application of recycled plastic waste. In 2017, Great Britain alone utilised 60,321 thousand tonnes of natural aggregate for use in construction, with 24,038 thousand tonnes of gravel and 24,632 thousand tonnes of sand used in concreting, comparable to 6,309 thousand tonnes of sand used for general building [2]. Mining of natural aggregate for use in concrete presents a significant environmental concern, not only for the energy- and emission-cost offered to the atmosphere in the extraction and transportation of said material, but simply through long-term availability and damage of a natural resource. Babafemi et al. [3] state the need for further research into the structural application of plastic in an effort "to grow confidence on the use of plastic aggregates in concrete" and begin development of industry-recognised guidelines for use in the construction industry. With this, the consumption of sand for concreting (typically used as a fine aggregate) exceeding that of gravel (typically the coarse aggregate in the concrete mix), along with plastic already utilised at present in non-structural applications, the implementation of plastic as a fine aggregate replacement in the development of a structural concrete, is a topic highlighted for consideration as a viable solution for recycling waste plastic at landfill.

Some of the main mixed plastic materials being utilised as fine aggregate replacements are:

A. Polythene Terephthalate (PET)

In some cases PET was utilised as fine aggregate e.g. Saxena et al. [4] undertook an experimental study looking at the properties of concrete under impact loading when fine aggregate in the concrete mix was replaced by recycled waste plastic. Waste PET bottles and cans were recycled and shredded into both fine and coarse aggregate, with fine plastic aggregate (FA) replacement noted to range in particle size from 0 to 4.75 mm, replacing sand at increasing 5% increments from 0 to 20%. A control mix, along with four FA replacement mixes were cast into three 100 mm^3 cubes and 100 x 75 mm cylinders, with the average compressive strength

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of concrete cubes read at 7, 28 and 90 days. Findings demonstrated a typical general decline in compressive strength as the percentage of plastic in the concrete mix increased. Compressive strength at 7 days curing was given as 17.8 MPa for the control mix, and 3.6 MPa for 20% plastic replacement – a decline of 14.2 MPa from control. Readings taken at 28 and 90 days curing further demonstrated the decline in compressive strength as plastic was introduced. The authors note that the smooth surface of the plastic aggregate used in the study was the "probable cause" for a poor cohesive bond experienced between the plastic aggregate and cementitious material, further noting voids created in the mix as a result of the poor cohesion provided "faster breaking of concrete edges during compressive loading".

As a contrast to [4], [5] utilised a much higher incremental aggregate replacement level of 25% to assess the influence of two forms of recycled waste as partial and full replacement of fine aggregate in the concrete mix. Chopped PET bottles and saw dust were utilised separately as replacements for sand at aggregate sizes noted by the authors as 0 to 4 mm, with the demonstrating and noting that workability of plastic-containing concrete mixes increased as plastic content increased. Following the casting of a control mix, mixes using replacement aggregate consisted of partial 25, 50, 75% replacement levels, and full 100% replacement, with mix coding following suit to reflect these increasing 25% plastic aggregate increments - PETPC1 to PETPC4, respectively. A selection of both fresh and mechanical properties of the concrete mixes were analysed, including compressive strength tested at 14 days curing on 70 mm^3 cube samples. The control mix achieved a compressive strength value of 47.90 MPa, whereby, despite a significant rise in compressive strength realised for the PETPC2 (containing 50% PET) - given as 54.32 MPa (an increase of 13.4% compared to control) – and marginal rise in PETPC3 (containing 75% PET) – given as 48.73 MPa (an increase of 1.7% compared to control) - the author notes a general trend of declining compressive strength as PET increased in the concrete mix; upon further inspection, however, a decline in compressive strength only occurred at either end of the PET replacement spectrum – declining from the control mix at partial (25%) and full (100%) replacement rates. The authors highlight a delay in the appearance of cracks under what was ultimately the maximum compressive force applied to the plastic containing cube samples, stating these were "slowly developed without destroying the sample" after an observed "elastic shortening and a swelling of the samples".

B. PET, Polyethylene (PE) and Polypropylene (PP)

In some other studies PET, PE and PP were utilised as fine aggregates. Thorneycroft et al. [6] undertook a regimented study incorporating five forms of recycled plastic as fine aggregate replacement across both granular and fibre morphologies. Performance of the concrete mix design was assessed with recycled plastic consisting of a set 10% partial replacement level of sand volume - a level determined from experimental mixes prior to the study. PET, High-Density Polypropylene (HDPP), High-Density Polyethylene (HDPE), Polypropylene Multifilament Fibres (PPF), Polypropylene Strips (PPS) were plastics assessed in the study, whereby three 100 mm^3 cubes and 100 mm diameter cylinders were cast as a control and 10 plastic-infused concrete mixes. Compressive strength testing was undertaken at 14 days curing with the control mix achieving 53.8 N/mm^2.

Particle sizes for PET, HDPP and HDPE all ranged from 0 to 4 mm, with PPF and PPS sized as fibres – Length = 20 mm, Diameter = 0.05 mm – and strips – Length = 20 mm, Width = 3 mm – respectively. The first three PET mixes (PET1, PET2, PET3) all demonstrated average compressive strength readings greater than 51.5 N/mm^2, where notably, PET1 with plastic particles graded to replicate that of sand, demonstrated a compressive strength value of 54.4 N/mm^2 – an increase of 1.2% (or 0.6 N/mm^2) compared to the control mix. HDPP1 however, replicating the particle size of PET3, and HDPE1 - shredded to 4 mm diameter particles - suffered a 12.6% reduction to 47.0 N/mm^2, and 15.0% reduction to 45.6 N/mm^2, respectively, when compared to the control mix. Where PPF1 demonstrated a significant reduction of 37.7% in compressive strength compared to the control mix, the 10% replacement rate caused the fibres to become "entangled" and thus demonstrate poor workability and low density; PPF2 was subsequently established to address the poor workability of PPF1, using a 0.64% plastic replacement rate to achieve the perceived workability required, offering a compressive strength value of 54.5 N/mm^2 (a 1.4% increase on the control mix), and 62.7% increase on PPF1 - this mix was disregarded however due to the highlighted complexity of manufacturing the fibres for use.

PPS1 was cast to compensate for the workability of PPF2 and compressive strength of PPF1. PPS1 demonstrated a suitable middle-ground with a compressive strength output of 52.2 N/mm^2, being a minor 2.9% reduction on the control mix. Finally, Thorneycroft et al. [6] analysed the impact of surface treatment of PET particles in relation to compressive strength. 8 PET4 (treated) and PET5 (treated and washed) were finally assessed and offered a significant 78.1% and minor 1.9% reduction in compressive strength compared to the control mix. The authors summarised the study's findings, stating "it is feasible to produce structural grade concrete mixes with 10% sand replacement".

C. PET and PE

Research to the date of 2018 has predominantly reflected the use of PET and PE as aggregate replacements in the concrete mix [7]. PP, as the world's most demanded plastic [8] not only requires continual innovation for application of recycled material, but also "consistent markets for varying quality levels of PP" [9]. With this, there has been a recent increase in literature addressing concrete as a consideration for the application a reuse of recycled PP. As to that of Thorneycroft et al. [6], plastic fibre as a fine aggregate replacement, notably shorter in length and of a different plastic type however, is a concept further investigated by other researchers. Smarzewski [10] studied the flexural toughness of high-performance concrete using Basalt (B) and PP fibres, both in conjunction, and separately to one another, as partial replacements for sand in the concrete mix. Basalt and PP fibres were utilised across 11 concrete mixes, including the control mix; where PP was used separately in mixes P1 and P2 at 1% and 2% replacement levels respectively, B and P used in combined mixes replacing sand followed coding of 'fibre type' then 'percentage of sand replaced' (e.g. Mix 'B0.75P0.25' contained 0.75% Basalt and 0.25% PP fibres), reordered to ascend in relation to PP content. The authors note the use of 20 L/m^3 superplasticizer as a means of ensuring good workability of fresh concrete when plastic fibres were added to the concrete mix, noting the plastic fibres created a "network structure", restricting segregation and flow, ultimately increasing mix viscosity and decreasing concrete slump [10].

A diversity of both basic and mechanical tests, including compressive strength testing, were undertaken on a total of 66 100 mm^3 cube samples allowed to cure for 28 days. At all sand replacement levels, irrespective of fibre type, the compressive strength of the concrete mix declines. When analysing mixes containing PP fibres however, there is a distinct positive correlation between increasing compressive strength and increasing content of these fibres up to a replacement level of 1%. It can also be seen, and is noted by Smarzewski [10], that, despite the decline experienced generally, compressive strength peaked for all mixes in one of the mixes containing only PP fibre – mix P1 - at 119.60 MPa (a small decline of 9% to that of the control mix); increasing the replacement percentage of PP fibres thereafter results in an addition decline in compressive strength of the mix. With this, the findings of Smarzewski [10] demonstrate that a decline in compressive strength of less than 10% can be achieved when replacing fine aggregates in the concrete mix up to 1% with PP fibres.

D. PP, PE, Polystyrene (PS) and Polyvinyl Chloride (PVC)

Jacob-Vaillancourt and Sorelli [11] studied the viability of using plastic aggregate as a partial replacement for sand in the development of an environmentally responsible concrete. In the study, the authors assessed the influence of not only plastic type, but replacement percentage, impurity level, and the timeline diversification upon processing of the plastic on the basic properties of concrete. A complex mix design was structured for the study, whereby mixed plastic packaging was pulled from the recycling materials stream, further sorted via infrared optical sorting and identified as 5 variations: PP, PE, PS, PVC and 'others'. A control mix was established with all 5 variations of plastic aggregate then utilised separately in their own mix designs, recombined into a mixed sample (MIX) noted by the authors to host between 56% and 62% PP, as well as into a sample combining both PS and PVC (PS-PVC).

After 28 days of curing, the concrete cylinder samples (Height = 150 mm, Diameter = 75 mm) were tested under the compression machine to obtain their compressive strength. MIX containing concrete mixes were implemented using coarse plastic aggregate at 5, 10 and 20%, as well as a graded plastic aggregate mix at 10% replacement level for sand; an air-reducing agent (ARA) was then introduced for a coarse plastic aggregate mix at 20% replacement of sand. They [11] note that for the MIX containing concrete mixes, increasing plastic aggregate content reduced compressive strength, with the 20% replacement level proving the most extreme reduction in compressive strength of 46.9% compared to the control mix – dictated by, in addition to content volume, "weakened interfaces" between plastic aggregate and cement and increase in air content. Concrete mixes that isolated the type of plastic were utilised as coarse aggregate at a 20% replacement level of sand, whereby the authors note variation of the type of plastic used in the mix has a significant effect on the compressive strength of the concrete mix, offering a range of reduction in relation to the control mix of 13 to 38%; upon inspection of graphical presentation of the results, it can be seen that all types of plastic experienced a decline in compressive strength compared to the control mix, with the best smallest reduction experienced with PVC (approx. 6.5 MPa), then PP and MIX (approx. 10 MPa), PE (approx. 11.5 MPa) and PS (approx. 16.5 MPa).

E. Summary

It can be concluded that from the reviewed researches, a prevalent trend is apparent whereby a decline in compressive strength is experienced as plastic aggregate is utilised as a fine aggregate replacement (typically to that of sand) in the concrete mix design. This decline appears irrelevant of plastic type, and typically worsens with increasing levels of plastic in the concrete mix, however PP used separately and PS and PVC used in combination offer the most promising reductions, generally where plastic particle size moves towards the uniform grading of the fine aggregate it replaces. Workability worsens with the addition of plastic to the concrete mix, whereby hardened bulk density reduces to offer considerably lighter concretes, both characteristics intensify with increasing plastic levels in the mix. No advantage was seen from the research reviewed for treatment of the plastic aggregate surface prior to use in the concrete mix, despite dominate themes of increased porosity and increasing air content present in the microstructure of the mix when plastic aggregate replaces sand; themes suggested by the vast majority of authors reviewed look to closely link findings to the poor cohesive capability of the hybrid aggregate blend and cementitious binding agent experienced, thus creating weak failure pockets within the concrete 'structure'. Whilst this decline in compressive strength is typical, it is not assured – shown through presented findings offering increases from baseline control mixes containing no plastic aggregate of over 1.5%, and, in one instance, that of an over 13%. It appears that morphology of plastic aggregate has an impact on the compressive strength of the concrete mix; however this is not distinct from the research reviewed. It can be said however that for granular shaped plastic, a fine aggregate replacement level of 10% proves optimal for mitigating any reduction in compressive strength experienced; replacement of fine aggregate with plastic fibres appears possible up to a dosage level of 1% without any significant reduction in compressive strength of the concrete mix. The current study therefore, will focus predominantly on the influence of PP as a fine aggregate replacement (by mass), on the mechanical property compressive strength, workability and properties of fresh - hardened concrete and bulk density of the concrete mix.

II. Methodology

A. Concrete Mix Design to British Standards

A reference concrete mix was designed in accordance with British Standards Institution [12]-[15] and The Concrete Society [16] in order to achieve an ST5 standardised prescribed concrete, suitable for "House and Garage Ground Floor Slabs", "fully nominally reinforced, either ground bearing, suspended or over sub-floor voids" [12]. A recommendation was offered for the reference mix to achieve a slump class S2 (50 to 90 mm) and to give an assumed strength class of C20/25 [12]. With the year 2017/18 demonstrating 42,652 housing starts – the largest since 2010 – and the period of April-September for 2018/19 offering 15,766 starts already, exceeding that of 2017/18 at 13,685 starts, respectively [17], the ST5 standardised prescribed concrete mix was selected and designed to offer a justified, practicality while meeting the requirement of the structural application, for plastic-containing concrete mixes. The Reference Mix design can be seen in Table I per 1.0 m^3 of concrete, Table II per 150 mm^3 of concrete, and Table III per batch of concrete.

B. Pilot Study

A pilot study was undertaken as a means of ironing out teething problems that may have arisen during the study's main experiments. Suitability of the experimental methodology was assessed, along with trial concrete batches for both the designed reference mix and the first-proposed plastic-containing mix (PP2.5), aimed at establishing whether the desired S2 slump class workability would be achieved.

TABLE I
Reference Concrete Mix Design to British Standards – Quantities per 1.000 m^3 of Concrete

W/C	Total weight	Water		Cement		Coarse Aggregate		Fine Aggregate		Plastic Aggregate		
Ratio	kg	% of Mix	L	% of Mix	kg	% of Mix	kg	% of Mix	kg	% of Mix	% of Fine Agg	kg
0.56	2385.00	8.81	210.00	15.72	375.00	49.06	1170.00	26.42	630.00	0.00	0.00	0.00

TABLE II
Reference Concrete Mix Design to British Standards – Quantities per 150 mm^3 of Concrete

W/C	Total weight	Water		Cement		Coarse Aggregate		Fine Aggregate		Plastic Aggregate		
Ratio	kg	% of Mix	L	% of Mix	kg	% of Mix	kg	% of Mix	kg	% of Mix	% of Fine Agg	kg
0.56	8.05	8.81	0.71	15.72	1.27	49.06	3.95	26.42	2.13	0.00	0.00	0.00

TABLE III
Reference Concrete Mix Design to British Standards – Quantities per Batch of Concrete

W/C	Total weight	Water		Cement		Coarse Aggregate		Fine Aggregate		Plastic Aggregate		
Ratio	kg	% of Mix	L	% of Mix	kg	% of Mix	kg	% of Mix	kg	% of Mix	% of Fine Agg	kg
0.56	72.44	8.81	6.38	15.72	11.39	49.06	35.54	26.42	19.14	0.00	0.00	0.00

C. Reference Mix

During the batching of the reference mix (as per Table IV), all materials were mixed with water added in 0.5 L increments. It was determined that at 5.50 L water (0.88 L less than designed), the batch of concrete visually hosted the workability of a concrete mix too wet to be classed as an S2 slump; slump test results at this stage confirmed visual assumptions, offering three 'shear' slumps in a row. At this point, engineering judgement was used to stiffen the reference mix in order to induce the workability required. Instead of solely increasing the cement content of the mix, an approximate mix ratio was taken from the Reference Mix Design for the addition of cement, coarse and fine aggregate, whilst maintaining the 5.50 L water already mixed (w/c ratio thus reduced from 0.56 to 0.44). Despite not in keeping with a generally prescribed concrete mix ratio of 1:2:4 [18], Tables I-III show an approximate mix ratio between reference mix materials (excluding water) of 1:2:3 (15.72%: 26.42%: 49.06%) for cement: fine aggregate: coarse aggregate. Materials were therefore added as cement 1 kg: fine aggregate 2 kg: coarse aggregate 3 kg, and subsequently mixed together with the existing reference batch of concrete; slump test results confirmed that the material adjustment had stiffened the reference mix as intended, producing a slump of 50 mm and thus S2 slump class.

D. Plastic-Containing Mixes

Following revisions and confirmation of the required workability, the reference mix design was used as the basis for the design of the first-proposed plastic-containing mix (PP2.5). Fine aggregate (sharp sand) was replaced at a rate of 2.50% by mass using plastic aggregate and batched by hand. The mixability of the plastic aggregate with other materials was deemed acceptable, however assessment of mix workability using the slump test on two occasions, demonstrated the mix as hosting a 20 mm slump, and thus S1 slump class. It was proposed at this stage that, in order to assess the validity of workability results offered from the PP2.5 mix, and to confirm workmanship relating to uniform mixing and distribution of batched materials, a marginal increase in plastic aggregate of 0.50% (as opposed to an additional 2.50% for the second-proposed plastic-containing mix), thus achieving a concrete mix containing 3.0% plastic by fine aggregate mass (PP3.0), would be implemented. It was proposed that the PP3.0 mix offer a stiffer mix and reduced slump measurement (e.g. < 20 mm) to that of the PP2.5 mix, then the additional plastic aggregate is the variable influencing workability, and the PP2.5 workmanship was sufficient. The PP3.0 mix was batched by hand as described above using the amended reference mix as a basis for design. Fine aggregate was replaced by mass at a rate of 3.0% plastic aggregate. Slump test results demonstrated on two occasions that workability of the mix was of an S1 slump class (10 mm). These workability results confirm the validity of slump results from the PP2.5 mix, that workmanship and material distribution was sufficient and uniform, and finally, the additional plastic aggregate stiffened the concrete mix further.

E. Experiment

1. Materials

Concrete mixes batched in this study were prepared using a Portland-Limestone Cement CEM II/A-L 32,5 R – Tarmac, 'Blue Circle Portland-Composite Cement' [19] - as a cementitious binding agent, confirmed by Tarmac [20] to conform to the physical property and chemical composition requirements stated in British Standards Institution [21], and thus not exceeding 6-20% limestone content [21]. Main constituent properties the cement used in this study are shown in Table VII. The fly ash used in this study was donated to the University of West London by Omni-Cem [22] from the Ratcliffe-on-Soar power station, Nottingham, England. Chemical constituent properties the fly ash used in this study are shown in Table VIII. The objective for the use of the aggregate materials in this study was to create a well graded mix, irrelevant and/or despite, the use of plastic replacement. With this, coarse aggregate used in the study's concrete mix batching was Gravel – Travis Perkins, 'Gravel and Pea Shingle Trade Pack 10 mm' [23] - ranging in particle size from 4 mm to 10 mm, with no aggregate particle exceeding 10 mm, and conforming to British Standards Institution [15]. Fine aggregate used in the study was a Quartz Sharp Sand – Travis Perkins, 'Sharp/Grit Sand' [24] – ranging in particle size from 0 mm to 4 mm, with no aggregate particle exceeding 4 mm, conforming to British Standards Institution [15], whereby typical morphology of sharp sand particles was "sub angular to rounded" [25]. Both coarse and fine natural aggregates were used in their saturated state immediately following delivery and storage outside in the building merchant's facility. Plastic aggregate used as the fine aggregate (sharp sand) replacement in plastic-containing concrete mixes was a proprietary recycled PP – Axion Group 'Axypoly ABS52' [26] - nominally manufactured into a cylindrical particle size of 3 mm x 2 mm, smooth in surface texture. Material properties of coarse, fine and plastic aggregates are shown in Table IX, with visual confirmation of particle size and morphology shown in Fig. 3.

2. Concrete Mix Design Procedure

In this study, six plastic-containing concrete mixes were batched using PP as a partial replacement by mass of fine aggregate in the mix (sharp sand). Following the findings of the pilot study, PP content of plastic-containing concrete mixes increased incrementally at a rate of 0.50% and in dosages from 0.50% to 3.00%, with coding for these mixes following from PP0.5 to PP3.0. Moreover, a 'control' concrete mix was batched as per the amended pilot study reference mix, providing a base of comparison for further concrete mixes containing plastic. In order to improve the issue of reduced workability at higher PP dosages evidenced in the pilot study, another mix (PP3.0FA) was added which included a 10.00% partial replacement by mass of cement using fly ash. As stated by [27], the addition of 10% of fly ash should allow a water reduction of at least 3% to concrete mixes. Water/cement ratio (w/c) was kept consistent at 0.44 throughout all mixes in this study. The mix proportions for all concrete mixes batched in this study are summarised in Table IV per 1.000m^3 of concrete, Table V per 150 mm^3 of concrete, and Table VI per batch of concrete. (Please note, for simplification of discussion hereafter, reference to the use of plastic aggregate in this study is made simply as a percentage - e.g. PP1.0 = 1.00% plastic aggregate and reflects the use of plastic aggregate as a fine aggregate replacement by mass in the mix only, and not use of plastic aggregate as a replacement percentage of the overall concrete mix design.)

TABLE IV
MAIN STUDY CONCRETE MIX DESIGN – ALL MIXES – QUANTITIES PER 1.000 M^3 OF CONCRETE

Mix No.	Mix code	W/C	Total weight	Water		Cement		Coarse Aggregate		Fine Aggregate		Plastic Aggregate			Fly Ash		
		Ratio	kg	% of Mix	L	% of Mix	kg	% of Mix	kg	% of Mix	kg	% of Mix	% of Fine Agg	kg	% of Mix	% of Cement	kg
1	Control	0.44	2551.44	7.10	181.07	16.00	408.2	49.68	1267.49	27.23	694.65	0.00	0.00	0.00	0.00	0.00	0.00
2	PP0.5	0.44	2551.44	7.10	181.07	16.00	408.2	49.68	1267.49	27.09	691.18	0.14	0.50	3.47	0.00	0.00	0.00
3	PP1.0	0.44	2551.44	7.10	181.07	16.00	408.2	49.68	1267.49	26.95	687.70	0.27	1.00	6.95	0.00	0.00	0.00
4	PP1.5	0.44	2551.44	7.10	181.07	16.00	408.2	49.68	1267.49	26.82	684.23	0.41	1.50	10.42	0.00	0.00	0.00
5	PP2.0	0.44	2551.44	7.10	181.07	16.00	408.2	49.68	1267.49	26.68	680.76	0.54	2.00	13.89	0.00	0.00	0.00
6	PP2.5	0.44	2551.44	7.10	181.07	16.00	408.2	49.68	1267.49	26.55	677.28	0.68	2.50	17.37	0.00	0.00	0.00
7	PP3.0	0.44	2551.44	7.10	181.07	16.00	408.2	49.68	1267.49	26.41	673.81	0.82	3.00	20.84	0.00	0.00	0.00
8	PP3.0FA	0.44	2551.44	7.10	181.07	14.40	367.41	49.68	367.41	26.41	673.81	0.82	3.00	20.84	1.60	10.00	40.82

TABLE V
MAIN STUDY CONCRETE MIX DESIGN – ALL MIXES - QUANTITIES PER 150MM^3 OF CONCRETE

Mix No.	Mix code	W/C	Total weight	Water		Cement		Coarse Aggregate		Fine Aggregate		Plastic Aggregate			Fly Ash		
		Ratio	kg	% of Mix	L	% of Mix	kg	% of Mix	kg	% of Mix	kg	% of Mix	% of Fine Agg	kg	% of Mix	% of Cement	kg
1	Control	0.44	8.61	7.10	0.61	16.00	1.38	49.68	4.28	27.23	2.34	0.00	0.00	0.00	0.00	0.00	0.00
2	PP0.5	0.44	8.61	7.10	0.61	16.00	1.38	49.68	4.28	27.09	2.33	0.14	0.00	0.01	0.00	0.00	0.00
3	PP1.0	0.44	8.61	7.10	0.61	16.00	1.38	49.68	4.28	26.95	2.32	0.27	0.00	0.02	0.00	0.00	0.00
4	PP1.5	0.44	8.61	7.10	0.61	16.00	1.38	49.68	4.28	26.82	2.31	0.41	0.01	0.04	0.00	0.00	0.00
5	PP2.0	0.44	8.61	7.10	0.61	16.00	1.38	49.68	4.28	26.68	2.30	0.54	0.01	0.05	0.00	0.00	0.00
6	PP2.5	0.44	8.61	7.10	0.61	16.00	1.38	49.68	4.28	26.55	2.29	0.68	0.01	0.06	0.00	0.00	0.00
7	PP3.0	0.44	8.61	7.10	0.61	16.00	1.38	49.68	4.28	26.41	2.27	0.82	0.01	0.07	0.00	0.00	0.00
8	PP3.0FA	0.44	8.61	7.10	0.61	14.40	1.24	49.68	4.28	26.41	2.27	0.82	0.01	0.07	1.60	10.00	0.14

TABLE VI
MAIN STUDY CONCRETE MIX DESIGN – ALL MIXES – QUANTITIES PER BATCH OF CONCRETE

Mix No.	Mix code	W/C	Total weight	Water		Cement		Coarse Aggregate		Fine Aggregate		Plastic Aggregate			Fly Ash		
		Ratio	kg	% of Mix	L	% of Mix	kg	% of Mix	kg	% of Mix	kg	% of Mix	% of Fine Agg	kg	% of Mix	% of Cement	kg
1	Control	0.44	77.50	7.10	5.50	16.00	12.40	38.50	12.40	27.23	21.10	0.00	0.00	0.00	0.00	0.00	0.00
2	PP0.5	0.44	77.50	7.10	5.50	16.00	12.40	38.50	12.40	27.09	20.99	0.01	0.50	0.11	0.00	0.00	0.00
3	PP1.0	0.44	77.50	7.10	5.50	16.00	12.40	38.50	12.40	26.95	20.89	0.27	1.00	0.21	0.00	0.00	0.00
4	PP1.5	0.44	77.50	7.10	5.50	16.00	12.40	38.50	12.40	26.82	20.78	0.41	1.50	0.32	0.00	0.00	0.00
5	PP2.0	0.44	77.50	7.10	5.50	16.00	12.40	38.50	12.40	26.68	20.68	0.54	2.00	0.42	0.00	0.00	0.00
6	PP2.5	0.44	77.50	7.10	5.50	16.00	12.40	38.50	12.40	26.55	20.57	0.68	2.50	0.53	0.00	0.00	0.00
7	PP3.0	0.44	77.50	7.10	5.50	16.00	12.40	38.50	12.40	26.41	20.47	0.82	3.00	0.63	0.00	0.00	0.00
8	PP3.0FA	0.44	77.50	7.10	5.50	14.40	11.16	38.50	11.16	26.41	20.47	0.82	3.00	0.63	1.60	10.00	1.24

TABLE VII
MAIN CONSTITUENT PROPERTIES OF CEMENT USED IN THIS STUDY [21]

Property	Cement (Quantity, %)
Clinker (K)	80-94
Limestone (L)	6-20
Minor Additional Constituents	0-5

TABLE VIII
MAIN CHEMICAL CONSTITUENT PROPERTIES OF FLY ASH USED IN THIS STUDY [22]

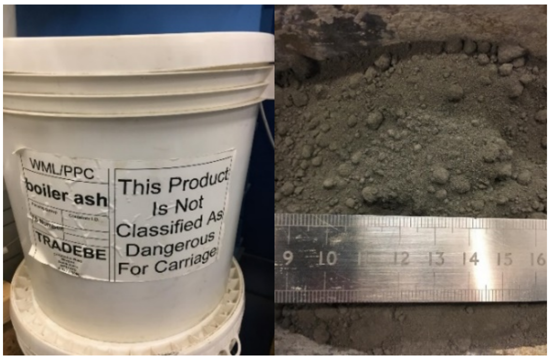
Property	Fly Ash (Quantity, %)
Water soluble chloride	<0.01
Acid soluble sulphates	0.72
Total sulphur	0.37
Calcium oxide	5.67
Magnesia	2.53
Silica	42.69
Ferric oxide	9.19
Alumina	23.09
Potassium oxide	2.27
Sodium oxide	0.72
Titanium dioxide	1.01
Others	11.73

TABLE IX
MATERIAL PROPERTIES USED IN THIS STUDY

Category	Material	Particle Size (mm)	Bulk Density (kg/m^3)	Reference
Cementitious Binding Agent	Portland-Limestone Cement	n/a	1440	[18]
Cementitious Binding Agent	Fly (Boiler) Ash	n/a	1300	[16]
Fine Aggregate	Sharp Sand	< 4mm	1250	[18]
Coarse Aggregate	Gravel	4-10mm	1200	[18]
Plastic Aggregate	PP	2x3mm	1075	[26]

Following the batching of each concrete mix, the 'Slump Test' was implemented to assess the workability of the concrete – "the ease of placing and compacting concrete" [28] in accordance with British Standards Institution [29] using the 'Ele International Slump Test Kit BS & ASTM 34-0192' [30]. Afterwards, specimens were cast into 150 x 150 x 150 mm steel casting moulds – Ele International '34-4670 – 150 mm Cube Mould 2-Part Clamp Type, Cast Iron Construction' [31] - as shown typically using the Control mix in Fig. 4. Concrete from the batch was sampled as per previous notes and placed into each cube mould in three approximate layers of 50 mm, tamped for a minimum of 40 times per layer, and finally vibrated on a vibrating table – Controls Group 'Vibrating Table 55-C0161/LCZ' until air bubbles rising to the surface of the moulds reduced significantly.

(a) Cement Packaging (b) Cement Particle Size



(c) Fly Ash Packaging (d) Fly Ash Particle Size

Fig. 1 Cementitious Binding Agent Materials - Product Details and Particle Sizes

Fig. 2 (a) Coarse Aggregate

Fig. 2 (b) Fine Aggregate

Fig. 3 Plastic Aggregate Material

Fig. 4 Steel Cube Moulds used to Cast Concrete Specimens

Specimens were cured in two large curing tanks – Ele International, Large Curing Tank 34-6575 Series [32] - maintained at a consistent 22.0 °C water temperature for their respective curing durations (7 or 28 days), and cured till immediately prior to further testing.

3. Testing

At each of the respective curing days, being 7- and 28-days, and following assessment of cube specimen densities, specimens were tested for compressive strength using the Ele International 'ADR-Auto V2.0' Compression Testing Machine [33] - outlined in British Standards Institution [34] and shown in Fig. 5 - set to a Loading Pace Rate of 13.50kN/s. All procedures for compressive strength testing were undertaken in accordance with British Standards Institution [35].

Fig. 5 Compressive Strength Testing Machine

III. Results and Discussion

A. Workability

Workability of control and plastic-containing concrete specimens (including PP3.0FA) are shown quantitatively in Table X, visually as concrete slumps in Fig. 6.

With the recommended workability for the ST5 Standardised Concrete Mix design in the British Standards, in this study the slump test is considered as an S2 slump class (slump between 50 mm and 90 mm). The control mix was thus established to achieve a workability within the S2 slump class – being 50 mm - as a base of comparison for plastic containing mixes.

Workability of fresh concrete typically decreased with the addition of plastic to the concrete mix. Workability of plastic-containing mixes (excluding PP3.0FA) offered a slump range of 10-50 mm and average slump of 32 mm. A reduction in workability therefore was experienced, ranging from 0-40 mm and offering an average slump reduction of 18 mm across these mixes. All plastic containing mixes (excluding PP3.0FA) therefore demonstrated a S1 slump class (between 10 and 40 mm) according to British Standards Institution [14] with mix PP0.5 the only mix offering an S2 slump class at 50 mm, matching that of the control mix.

Increasing plastic aggregate in the concrete mix coincided with a linear decline in workability. As seen in Fig. 7, as the level of replacement plastic aggregate was applied in 0.50% increments from 0.50%-3.00% in mixes PP0.5-PP3.0, respectively, workability declined in increments of 10 mm from the previous mix. It is generally found that increasing plastic in the concrete mix causes a gradual decline in workability [36], [10], [37], [5], [7].

Implementation of fly ash offered a mitigating effect on reductions experienced using plastic in the concrete mix. Moreover, concrete mix PP3.0, containing 100% cement, demonstrated a workability of a 10 mm slump, the addition of fly ash as 10% replacement of cement in mix PP3.0FA demonstrated a 200% increase in workability to that of PP3.0 at 30 mm, and 20 mm reduction on the control mix (compared to a 40 mm reduction from control to mix PP3.0). With this, using fly ash allowed an additional 1.00% of plastic aggregate to be applied to the plastic-containing concrete mix of equivalent workability – being mix PP2.0. Workability improvement is generally found in concrete mixes without plastic aggregate [39]-[41].

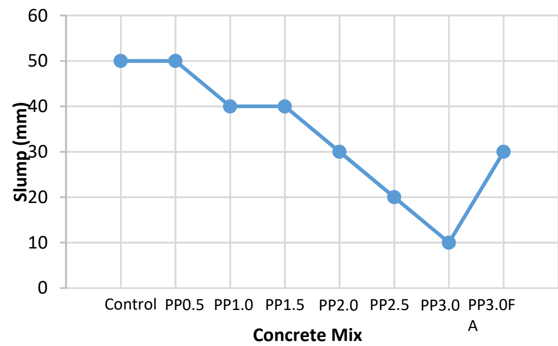
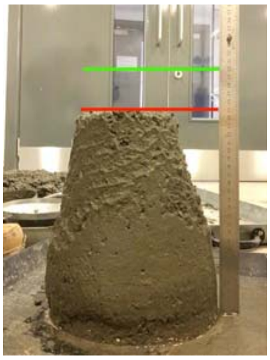
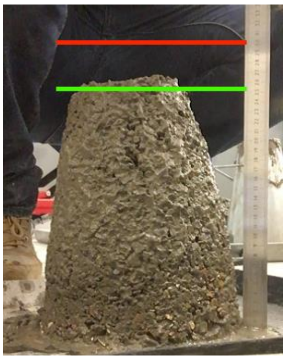


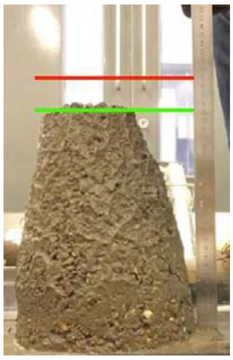
Fig. 7 Workability Results of All Concrete Mixes



(a) Control



(b) PP0.5



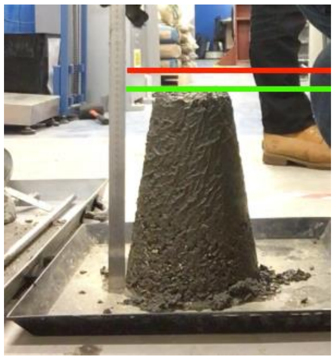
(c) PP1.0

(d) PP1.5

(e) PP2.0

(f) PP2.5

(g) PP3.0



(h) PP3.0FA

Fig. 6 Workability of Concrete Mixes – Slump Test Photographs

B. Compressive Strength

Compressive strength results of control and plastic-containing concrete specimens (including PP3.0FA) are shown in Table X and Fig. 8. Compressive strength findings for the three control mix specimens tested at 7-days curing ranged from 21.00 to 21.54 N/mm^2, and offered a mean compressive strength of 21.22 N/mm^2. The 28-day curing condition offered a range from 30.12 to 31.04 N/mm^2 and mean value of 30.50 N/mm^2. It was presented therefore that from 7- to 28-days curing, compressive strength developed and increased by a further 9.28 N/mm^2 (or 44% from 7- days). It should be noted that 25 N/mm^2 is the British Standards [12] requirement for the ST5 concrete mix design compressive strength and therefore, it was apparent that at 7-days curing, the control mix nearly achieved the compressive strength requirement set out in the British Standards, and at 28-days curing, exceeded this requirement.

Compressive strength of concrete specimens decreased with the addition of plastic at both 7- and 28-days curing. As shown in Fig. 8, compressive strength testing undertaken on plastic-containing concrete specimens (excluding PP3.0FA) demonstrated an average reduction of 4.55 and 5.77 N/mm^2 at 7- and 28-days curing in comparison to the control mix. At 7-days curing, compressive strength values ranged from 15.03 to 18.06 N/mm^2 and hosted a collective mean compressive strength of 16.67 N/mm^2. At 28-days curing, compressive strength ranged from 23.62 to 26.44 N/mm^2, offering a collective mean value of 24.73 N/mm^2. Therefore, it was evident that as curing time increased, compressive strength increased significantly, with an average increase of 48.59% from 7- to 28-days respectively, presented as an increase of 8.06 N/mm^2.

The declining compressive strength experienced in this study when plastic aggregate was added to the concrete mix, as well as the development of this mechanical property of concrete from 7- to 28-days curing, is trend consistent with the majority of previous research assessed [4]-[7], [10], [11], [36]-[38], [42], [43]. It can be said that from the current study, at the type, shape and morphology of the plastic used along with the hydrophobic nature of plastic generally, addition of plastic aggregate to the concrete mix interrupted the interfacial matrix within the concrete, offering an inevitable reduction in bonding of plastic and hydrated-cementitious material, leading to an enhancement of micro-cracks to failure under compressive loading [4], [6], [38], [42].

Compressive strength generally increased with the increasing levels of plastic aggregate in plastic-concrete mixes (excluding PP3.0FA), irrelevant of curing timeframe. At 7-days curing, compressive strength increased from 16.02 N/mm^2 for mix PP0.5 (containing 0.50% plastic) to 16.73 N/mm^2 for mix PP3.0 (containing 3.00% plastic), peaking at 18.06 N/mm^2 for mix PP2.5 (containing 2.50% plastic). At 28-days curing, values increased from 23.62 N/mm^2 for mix PP0.5 to 24.50 N/mm^2 for mix PP3.0, again peaking for mix PP2.5 at 26.44 N/mm^2.

With the overall increase in compressive strength experienced as plastic increased in the concrete mix, shown in Fig. 8, only 2 of the 5 plastic-containing concrete mixes (excluding PP3.0FA) demonstrated an increase from the previous mix at 7-days curing, however at 28-days curing, the opposite was apparent in which 3 out of the 5 mixes increased in compressive strength. This rise in compressive strength experienced in the current study with increasing levels of plastic aggregate in the concrete mix, is a finding contrary to findings of previous authors [3]-[5], [7], [10], [36], [37], [42]. Based on previous research, increasing levels of plastic in the concrete mix, along with the hydrophobic nature of plastic and characteristics of the plastic aggregate used as previously mentioned, should have further progressed the development of a porous concrete and production of air voids within the concrete mix [4], [6], [10], [38], [42], however it can be said that, since tension propagates failure in concrete [6], the increasing levels of plastic used in this study – despite being small increments of 0.50% - offered an increasingly elastic enhancement of the concrete mix during maximal compressive loading [5], [6].

TABLE X
STUDY RESULTS (MEAN VALUES PER CONCRETE MIX)

Mix Code	Workability	7 Day Curing Period		28 Day Curing Period	
	Slump (mm)	Density (kg/m^3)	Compressive Strength (N/mm^2)	Density (kg/m^3)	Compressive Strength (N/mm^2)
Control	50	2245.13	21.22	2251.25	30.50
PP0.5	50	2229.75	16.02	2230.78	23.62
PP1.0	40	2223.55	17.43	2226.70	24.80
PP1.5	40	2204.71	16.74	2211.62	25.23
PP2.0	30	2203.92	15.03	2215.82	23.78
PP2.5	20	2219.26	18.06	2144.60	26.44
PP3.0	10	2218.60	16.73	2223.58	24.50
PP3.0FA	30	2212.34	14.17	2234.62	20.85

It is possible that the enhanced elasticity of the mix is due to the foldability of the plastic [4] combined with the columnar shape of the aggregate to offer an absorption of additional compressive strength. It is also possible that the 2 mm x 3 mm particle size of plastic aggregate used, rather than developing further air voids as previously mentioned, actually minimised air voids during initial compaction of concrete into cube moulds, and offered a positive contribution to the overall grading of the aggregates in the concrete mix, shown in previous research [6], [38], [42], and the current study, to increase compressive strength.

In general, plastic-containing concrete mixes (excluding mix PP3.0FA) marginally failed to achieve the ST5 standardised prescribed concrete mix compressive strength requirement. At 28-days curing, the compressive strength of 25 N/mm^2 is required for classification of plastic-containing concrete mixes (excluding mix PP3.0FA) as hosting sufficient strength for an ST5 standardised prescribed concrete mix, failed to be achieved by an average of 0.27 N/mm^2 (or 1.1%). It was experienced however, that 2 out of the 5 mixes (excluding PP3.0FA) exceeded the 25 N/mm^2 requirement, with mix PP1.5 and PP2.5 achieving 25.23 and 26.44 N/mm^2, respectively. It can be said that, when considering the partial factors of safety applied to structural application of concrete, with the use of the plastic aggregate applied, and the compressive strength findings in the current study, replacing fine aggregate in the concrete mix by mass, can be applied up to a maximum of 3.0%, without a significant reduction in compressive strength of the concrete mix.

The use of fly ash as 10% partial replacement by mass of cement further reduced compressive strength. As seen in Fig. 8, at 7-days curing, mix PP3.0FA offered a compressive strength of 14.17 N/mm^2, being a 7.05 N/mm^2 (or 33.2%) reduction on the control mix, and a 2.56 N/mm^2 (or 15.3%) reduction on the concrete mix hosting the equivalent level of plastic and 100% cement - mix PP3.0. This trend continued at 28-days curing, when compared to the control mix, a 9.65 N/mm^2 (or 31.6%) reduction in compressive strength was experienced to 20.85 N/mm^2; interestingly, fly ash caused a similar reduction at 28-days curing to that of 7-days curing of 14.9% (or 3.65 N/mm^2) when compared to mix PP3.0. At both curing dates, the addition of fly ash caused the largest reduction in compressive strength of all mixes assessed in the current study. It was finally apparent that the early development of compressive strength was not significantly influenced with the addition of fly ash to the mix, and when compared to mix PP3.0, mix PP3.0FA slowed the development of compressive strength at 7-days by 0.32% with mix PP3.0 achieving 68.28% of the final 28-day compressive strength at 7-days curing, and mix PP3.0FA 67.96%, respectively.

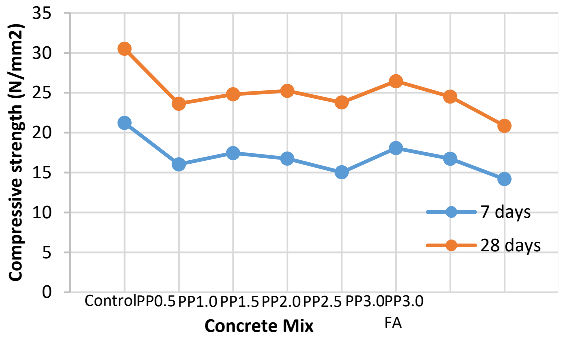
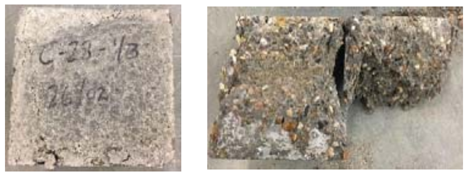


Fig. 8 Compressive Strength Results of All Concrete Mixes at 7- and 28-Days Curing

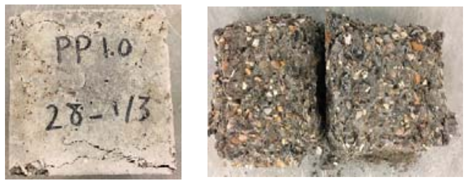
C. Plastic Particle Distribution

Concrete specimens cast in this study, broken in half following compressive strength testing at respective 7- and 28-days curing, can be seen typically in Fig. 9 at 28-days curing. Breaking of concrete specimens following compressive strength testing at both 7- and 28-days curing demonstrated that plastic aggregate used in this study was evenly distributed throughout each respective 150 mm^3 concrete cube. This finding suggests that the plastic aggregate used in this study was not affected by hand compaction, vibration, or curing conditions, and was evenly sampled following batching of each respective mix.

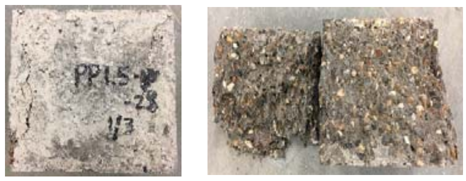


(a) Control

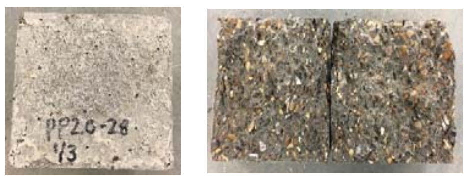
(b) PP0.5



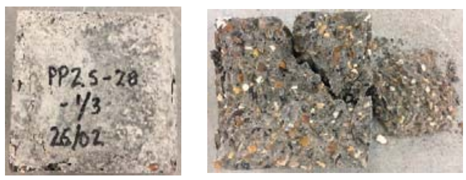
(c) PP1.0



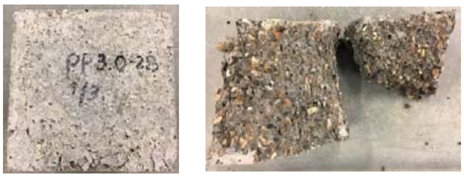
(d) PP1.5



(e) PP2.0



(f) PP2.5



(g) PP3.0

(h) PP3.0FA

Fig. 9 Breaking of concrete cubes – shown typically per mix at 28-days curing

IV. CONCLUSION

In this study, the influence of recycled PP plastic aggregate on the compressive strength and workability of concrete was assessed. Based on the results, the following conclusions are drawn:

- It is typically seen that workability is negatively affected with the addition of plastic aggregate, worsening further as additional plastic is incorporated into the concrete mix.
- The increased surface area of columnar-shaped, smooth-textured plastic aggregate used in this study, appeared to increase frictional resistance and viscosity within the mix matrix, thus limiting free movement between particles contained within the concrete mix, and reducing workability.
- The current study demonstrated a typical decline in compressive strength with the addition of plastic aggregate, despite this reduction generally mitigated as the level of plastic in the concrete mix increased.
- Two of the seven plastic-containing concrete mixes tested in the current study exceeded the ST5 standardised prescribed concrete mix compressive strength requirement at 28-days curing of 25 N/mm^2, being mix PP1.5 and PP2.5 (containing 1.50% and 2.50% plastic aggregate, respectively), whereby the remaining plastic-containing concrete mixes failed to achieve this requirement by an average of 0.27 N/mm^2.
- For all concrete mixes tested in the current study, breaking of hardened concrete cube specimens at both 7- and 28-days curing, demonstrated no bias distribution of concrete mix materials, including plastic aggregate.
- Whilst not the direct focus of the current study, it appears that the incorporation of fly ash as a partial replacement of cement in the concrete mix positively influences workability, however, unless incorporation of fly ash is managed carefully, as with traditional concrete containing only cement, the physical and chemical characteristics of fly ash can significantly, and negatively, influence the compressive strength of the concrete mix.

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