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Performance Evaluation of Environmentally Sustainable Precast Cement Concrete Paver Blocks Using Fly Ash and Polypropylene Fibre

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Abstract: Paver blocks are manufactured from zero-slump plain concrete, which is small element used for outdoor applications and flexible road surfaces. IS:15658 (2006) permits the use of 33- grade ordinary Portland cement (OPC) as the minimum for manufacturing paver blocks, but the usage of this type of cement is restricted in India nowadays. In this context, we have studied OPC 43-grade cement replaced by 30% Class F-grade fly ash and the addition of 0.0% and 0.5% polypropylene fibre (PPF) to evaluate the suitability of paver blocks in terms of the climatic conditions, movement of vehicles and road surfaces in India. The synergistic effect of the mechanical properties of paver blocks revealed that a 30% replacement of OPC with fly ash and 0.3% PPF is more suitable for the manufacturing of paver blocks. The obtained results from the reference mixes indicated that the mechanical properties of paver blocks have increased with respect to the age of the blocks. The present study is important for paver block manufacturers as it fulfils the mix design, strength and durability requirements for Indian roads associated with the utilization of waste materials such as fly ash. Additionally, the study will help the national economy increase by 20% in the future, along with the sustainability of virgin materials.

Keywords: fly ash; polypropylene fibre; cement; strength; waste management

1. Introduction

Concrete paving blocks were first produced in the United States in the 1960s for sidewalks, courtyards, driveways and parking areas [1]. Precast cement concrete paver blocks are solid; unreinforced products are made out of cement concrete with a low water–cement ratio. These are made in various dimensions with different concrete grades to fulfil the need for diversified environmental traffic conditions. Paving blocks are used for heavy-load pavements, low-speed, heavily trafficked urban streets and most recently airfield taxiways, industries, etc. [2]. Paver blocks are manufactured so that they interlock with each other while stationary to maintain structural strength. Paving blocks are produced in various shapes with a wide variety of dimensions [2]. The most commonly used interlocking paver block shapes are I-shape, zigzag, Colorado and Euphrates. In India, the Indian Institute of Technology (IIT) Kharagpur was the first to start researching and developing paver block pavements for practical applications in floor finishing and road surfacing.

Further, with the growth of industrialization in India, the demand for electricity generation has increased manifold. Thus, there is a need for many more electricity generation plants. Most of the plants are based on licensed technology and are unfit for low-grade Indian coal with high ash and moisture contents; therefore, the plants do not operate at maximum efficiency [3]. The electricity generation plants use coal as the energy substrate which results in the production of fly ash as a by-product. The fly-ash disposal is a burden for power generation plants. To facilitate fly-ash disposal, 30% of the OPC is replaced to manufacture paver blocks. The paver blocks are used for various traffic categories as per IS: 15658 (2006) [4]. The use of fly ash in concrete paver blocks as a partial replacement of the OPC is intended to reduce the cement particulate content and hence, the heat of the hydration, which results in economical durability. It will also help save energy during cement production. Due to the advances of industrialization worldwide, the production of electricity has increased manifold, resulting in the production of high fly-ash content at thermal power plants. The utilization of fly ash in the manufacturing of paver blocks would ensure safe and economical fly-ash disposal [5].

Although a few studies have reported a higher dosage of fly ash used in concrete, the optimum dosage has been recorded as 30% [5]. Fly-ash-based concrete paver blocks have the limitation of low tensile strength. To overcome this limitation, the addition of small percentages of polypropylene fibre by weight to the cementitious materials has been proposed. The study's potential significance is to reduce the problem of fly-ash disposal, save energy, improve the economics of road construction, and enable ductile paver blocks to use polypropylene for a longer span of time [6].

The microcrack formation in concrete at an early stage due to plastic shrinkage is also addressed with polypropylene fibres. The replacement of 30% OPC with fly ash and other materials has been reported in the literature [7]. Several studies have been carried out to explore the benefits of using various waste materials, such as fly ash [8], granite dust, marble dust [7], stone dust and glass powder [8], polypropylene fibre [1–3,8] and sisal fibre [9], for making paver blocks and thereby enhancing the properties of the developed product. Table 1 shows concrete and paver blocks prepared using various percentages of fly ash [FA] and/or polypropylene fibre [PPF], indicating the increasing interest in geopolymer-based concrete and paver blocks. In 1965, PPF was blended into concrete to construct blast-resistant structures for U.S. corps [10]. More recently there has been a need to introduce a material which is easily available and cost-effective in the construction industry [11]. Fibre increases the initial cost of the composite, so it is essential to use minimal fibre content in the composite. It is imperative to address the construction industry's economic challenges by substituting cement with any well-known abundantly available industrial by-product, such as fly ash, to improve the concrete's properties. PPF belongs to a family of synthetic fibres; as of today, polypropylene ranks fourth place among the other three classes of fibre: polyester, rayon and acrylics [12]. The inherent properties of fibre are being lightweight, cottony soft, durable and thermally insulated. Uygunoglu et al. [5] investigated the effect of OPC replaced by fly ash and 10%, 20%, 30% and 40% marble powder, respectively; the results showed that the compressive strength of concrete decreased while the replacement percentage of fly ash and marble powder increased.

Table 1. Concrete/paver blocks developed using percentages of fly ash [FA] and/or polypropylene fibre [PPF].

S. No.	% FA and/or PPF	Concrete/Paver Blocks	Remarks	References
	PPF and PET	Concrete of M40 grade	With the addition of fibersfibres in concrete, workability was reduced.	Singh and Goel [3]
	FA + PPF [25%, 50% and 0% to 0.3%]	Concrete of M40 grade	The value of compressive strength was 56.4 MPa and increased to 14.6% when added with 0.3% PPF as compared to concrete without PPF containing concrete.	Thirumurgan and Sivakumar [7]
	FA [20 to 40%]	Concrete of M30, M35, M40 and M50 grades paver blocks	Developed paver blocks resulting in reduced water to cementitious ratio.	Sachdeva et al. [9]
	FA+ waste glass equal ratio [0% to 40%]	Concrete of M40 grade Paver block	Optimum replacement was 20% for maximum compressive strength. AlsoAdditionally, strength increases with curing days for all mixes.	Santhosh and Talluri [10]
	FA+ [PPF + steel fibre in equal vol] [15% to 25% and 0.5% to 1%]	Concrete of M25 grade	Compressive strength increases with age in all the mixes and mix with 20% FA was optimum.	Dhillon et al. [11]
	FA + PPF [100% and 0.1% to 0.5%]	Paver blocks	0.2% PPF addition, gives had good results for abrasion resistance and flexural strength of 49.99 N/mm2 at 28 days.	Muhammed and Varkey [12]
	Metakaoline +PPF [0% to, 9% and 0.2% to 0.8%]	Concrete of M30 grade	Compressive strength increased with age. The maximum strength was at 0.2% addition of PPF. The value of compressive strength was 66.03 MPa for concrete with 8% metakaolin and 0.8% PPF.	Kaur et al. [13]
	FA+ Recron 3S [20% and 0% to 1%]	Concrete of M30, M35 grades	Increase in percentage of fiber, increasesfibre; increase in compressive strength. The value of compressive strength was 25 MPa with 1% PPF.	Rao et al. [14]
	FA [35% to 70%]	Concrete of M20, M50 and M70 grades	Maximum flexural strength was attained at 35% replacement level with 12% saving in cost.	Shrivastava and Bajaj [15]
	PPF + Glass fibre in the ratio of 75:25 [0.1% to 0.7 %]	Concrete of M25 grade	Maximum compressive strength with an optimum dose of 0.5% fibersfibres.	Singh and Kumar [16]
	PPF [0% to 2%]	Concrete of M30 and M40 grades	The value of compressive strength was 37 MPa for M30-grade concrete with 0.5% PPF.	Mohod [17]
	PPF [0.5% to 1.5%]	Concrete of M30 grade	Flexural strength of M30 -grade concrete werewas 2.89 to 3.09 MPa with PPF [0.5% to 1.5%]. The maximum flexural strength was obtained at 1.5% PPF.	Naraganti et al. [18]
	FA [0% to 40%]	Paver blocks	Flexural strength of 6 MPa at 7seven days attained the target value.	Karasava et al. [19]
	Waste marble [0 to 40 %]	Paver blocks	Compressive strength at high replacement level resulted in lower strength.	Gencel et al. [20]
	FA + PPF [50% to 60% and 0.9%]	Concrete of M35 gradesgrade	Better compressive strength was obtained at 50% level of replacement.	Chamundeswari et al. [21]
	FA + PPF [0%, 10%, 15%, 20% and 25%]	Concrete of M30 and M35 grades	Strength of the composite increases up to 10% level for smaller size particles of 53–75 μm.	Gummadi et al. [22]
	FA [20% to 50%]	Concrete M30, M35 and M40 grades,	Compressive strength decreases at early age and increases between 28 and 56 days.	Narendra [23]
	PPF [0.1% to 0.5%]	Concrete of M30 and M35 grades	Compressive strength increased with age in all the mixes and the optimum dose was 0.4%.	Kashiyani et al. [24]

Table 1. *Cont.*

S. No.	% FA and/or PPF	Concrete/Paver Blocks	Remarks	References
	PPF [0% to 0.35%]	Concrete of M25 grade	Maximum compressive strength of 38.10 MPa at 0.15% at 28 days.	Singh [25]
	FA + PPF [10% and 0% to 3%]	Concrete of M30 and M35 grades	Replacement of OPC by 10% FA in all the mixes. With 1.5% PPF dosage, the maximum compressive strength attained was 32.74 MPa.	Khan and Ahmad [26]
	PPF [0% to 0.5%]	Paver blockblocks	Compressive strength was 43.59 MPa with 0.4% PPF which was higher than standard specimen.	Anila et al. [27]
	Marble dust [0% to 10%]	Cube specimen	Compressive strengths are 16.05% and 18.69% in 7 days and 28 days, respectively, which were higher than without marble dust based concrete	Mishra et al. [28]

Santhosh and Talluri [10] evaluated paver blocks by replacing cement with fly ash and waste glass powder in equal quantities of 0%, 10%, 20%, 30% and 40% for M40-grade paver blocks and reported the optimal replacement as 20% for the maximum compressive strength. Additionally, the strength increased based on the curing days for all the mixes. Dhillon et al. [11] studied concrete by replacing OPC with 15%, 20% and 25% fly ash and adding steel and polypropylene fibres at 0.5% and 1%, respectively, by volume in M25-grade concrete; they reported that compressive strength increased with the age in all the mixes and the mix with 20% fly ash was the optimum. Muhammed and Varkey [12] investigated geo-polymer concrete paver blocks' properties by replacing OPC with 100% fly ash and adding polypropylene fibre in varying proportions from 0.1% to 0.5% and reported that compressive strength increased as the percentage volume fraction of PPF increased. Kaur et al. [13] studied the effect of metakaolin and polypropylene fibres on M30-grade concrete by replacing cement with metakaolin at 0%, 7%, 8% and 9% and polypropylene fibres at 0.2%, 0.5% and 0.8% and concluded that the compressive strength increased with aging. The maximum strength was at 0.2% PPF blending.

Ahmed et al. [29] reviewed fibre-reinforced polymer [FRP] concrete, which has the advantages of being economically efficient and sustainable, in that it uses corrosion-free FRP bars in marine environments.

Based on the relevant literature survey, it was reported that most of the investigations were carried out on concrete using various waste materials. Limited literature is available on paver blocks using waste materials. Most of the survey has been carried out by replacing OPC with a high fly-ash content volume. Polypropylene fibre has also been proposed to be added to fly ash concrete paver blocks to improve the ductility, which is an essential index of any road surface. Limited data is available on the durability properties of paver blocks. Because of the variations in Indian climatic conditions, the importance of freeze–thaw durability becomes much more critical [30]. To assess paver blocks' properties, prediction models are based on the fundamentals. The present research study has been conducted to address such gaps in the literature and to improve the quality and durability of paver blocks. Our idea is to use a waste material, i.e., fly ash, to potentially save costs and energy, lower CO_2 emissions during production and conserve raw materials for a longer span of time. The present study is carried out to investigate the various properties of manufactured paver blocks from concrete composites formed from conventional concrete by using fly ash as partial replacement of ordinary Portland cement [OPC] and the addition of polypropylene fibre in varying proportions.

2. Materials and Methods

2.1. Materials

Different materials were used in the manufacture of paver blocks of M30-, M35- and M40-grade designations and 43-grade OPC was procured from the local market of Patna conforming to IS: 8112 [31]. The results regarding the chemical properties are tabulated in Table 2. Natural river sand and artificial sand [stone crushed sand] with an IS sieve passing fraction of 4.75 are called fine aggregates. River sand procured from Patna, Bihar conforming to IS: 383 [32] was used for the conducted research. The sand was tested as per IS: 2386 [33] standard. The test results of the sieve analysis were obtained and physical properties were observed for fine aggregates. The physical properties of fine aggregates were bulk density (loose) (1567 kg/m^3), specific gravity (2.57) and water absorption (0.60%). Most of the aggregates retained on 4.75 mm IS sieve are known as coarse aggregates. These can be crushed or uncrushed gravel. In the present research, crushed stone aggregates were used having maximum nominal size of 10 mm, procured from a local market in Patna, Bihar, India. The coarse aggregates were tested according to [33].

Table 2. Chemical properties of fly ash.

S. No	Chemical Composition	Observed Values [% by Mass]
1.	Silicon dioxide +Aluminum oxide + iron oxide	93.27
2.	Silicon dioxide	59.78
3.	Aluminum oxide	27.92
4.	Iron oxide	5.57
5.	Calcium oxide	0.56
6.	Magnesium oxide	4.01
7.	Total sulphur	0.35
8.	Alkalis as sodium oxide	0.10
9.	Total chlorides	0.10
10.	Loss on ignition	1.90

Physical properties of coarse aggregates were analyzed and reported as follows: bulk density (loose) (1440 kg/m^3), specific gravity (2.63), water absorption (0.48%), impact value (14%) and abrasion value (19%). Fly ash was procured from Barh Superthermal Power Station, Barh, which is near Patna, Bihar. The specific gravity and class of fly ash were 2.08 and F-Type, respectively. The chemical properties of fly ash tested at the materials testing lab in Patna are given in Table 2. The physical parameters of chemical admixture were as follows: reddish-brown liquid appearance, relative density (1.08 + 0.01 at 25 °C]), pH > 6 and chloride ion content (<0.2 %). The recommended dosage of chemical admixture is 500 mL to 1500 mL per 100 kg of cement material. In the present study, the dosage of superplasticizer used was 500 mL per 100 kg of cementitious material. The brand name of PPF was Recron 3S (shown in Figure 1). The required quantity of PPF was soaked in water for a minute and then this water was added to the concrete batch and mixed to obtain excellent dispersion. The specifications of Recron 3S supplied by the supplier are reported in Table 3.

Table 3. Specifications of Recron 3S.

Property	Value
Length	12 mm
Fibre shape	Triangular
Gravity (Specific)	0.91
Diameter (Effective)	25–40 micron
Strength (Tensile, kg/cm^2)	4000–6000
Melting temperature	165 °C
Replacement rate	125 gm/50 kg cement

Figure 1. Polypropylene fibres.

2.2. Methods

The details of the procedure for manufacturing paver blocks and testing methods adopted for investigating the paver blocks are given here. The test procedures for determining strength (compressive and flexural) and durability properties, such as water absorption, are also delineated. The composite mixes of concrete were designed by replacing OPC with 30% fly ash as partial replacement and polypropylene fibre was added at 0.0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5% in each grade and with thickness of 60 mm and 80 mm. Block thickness and grades used for manufacturing paver blocks were as per IS: 15658 (2006) [4]. The specified grades and minimum thickness of blocks are M30 (50 mm), M35 (60 mm), M40 (80 mm), M50 (100 mm) and M55 (120 mm). The paver blocks' characteristics were adopted in the present study in accordance with IS: 15658 (2006) [4] and correction factor for paver Blocks (thickness and arris/chamfer). Detailed mixed design/procedures with calculation of strengths of studied paver blocks are given in Table 4.

2.2.1. Details of Paver Block Specimens

The paver block specimens were cast to assess their quality parameters in the fresh state and the hardened stage. Suitable care was taken for filling the moulds of specimens. The compressive strength, flexural strength and abrasion resistance of test specimens were analysed in triplicates for each age (7 and 28 days) with water absorption at 28 days. In each grade, 60 mm and 80 mm thick paver blocks were cast as per IS: 15658 (2006) [4], given in Table 4. The compaction factor test is normally used for low-slump concrete compacted by vibration as reported by Gambhir M.L. The ingredients of concrete composite for the manufacture of paver blocks were weighed and put in the mixture. First, coarse aggregate (10 mm size) and fine aggregate were mixed. Weighed cement was added in dry condition to the mixture. Fifty percent water was added to the mixture and uniformly mixed for one and a half minutes. The measured quantity of PPF soaked in the balanced water to have uniform dispersion in the mixture was added. Superplasticizer with some quantity of water was added to the whole mixture for uniform mixing. The mixer was run for another half a minute. The concrete composite was then taken out from the mixer. Compaction factor for the mixed quantity was observed. Cement slurry (with a 1:3 ratio of cement to sand) was put in the paver block moulds and kept on the vibrating table for subsequent filling. The paver block mould filled with concrete composite was allowed to vibrate on the table from one end to another end and the moulded paver blocks were taken for moist-curing by placing them in between plywood boards. After 24 h of moist curing, the paver blocks were de-moulded, named according to their grades and placed in curing chamber for subsequent curing till testing (Figure 2). The temperature during the curing periods in the tank was maintained at 23 ± 3 °C for 7 and 28 days.

Table 4. Final Mix Design.

Mix ID	Cementitious Material		Water	Fine Aggregate	Coarse Aggregate	SP	PPF	Water Cement Ratio
	Cement	FA						
	kg/m^3							
M30F30P0.0	269	116	152	953	879	2.08	0.000	
M30F30P0.1	269	116	152	953	879	2.08	0.385	
M30F30P0.2	269	116	152	953	879	2.08	0.770	
M30F30P0.3	269	116	152	953	879	2.08	1.155	
M30F30P0.4	269	116	152	953	879	2.08	1.540	
M30F30P0.5	269	116	152	953	879	2.08	1.925	0.43
M35F30P0.0	273	117	152	951	877	2.11	0.000	
M35F30P0.1	273	117	152	951	877	2.11	0.390	
M35F30P0.2	273	117	152	951	877	2.11	0.780	
M35F30P0.3	273	117	152	951	877	2.11	1.170	
M35F30P0.4	273	117	152	951	877	2.11	1.560	
M35F30P0.5	273	117	152	951	877	2.11	1.950	0.43
M40F30P0.0	293	125	152	926	875	2.25	0.000	
M40F30P0.1	293	125	152	926	875	2.25	0.418	
M40F30P0.2	293	125	152	926	875	2.25	0.836	
M40F30P0.3	293	125	152	926	875	2.25	1.254	
M40F30P0.4	293	125	152	926	875	2.25	1.672	
M40F30P0.5	293	125	152	926	875	2.25	2.090	0.40

Note: Fly ash (FA); Super plasticizer (SP); polypropylene fibre (PPF). M30F30P0.1: M is for mix; 30 is fck; F30 for FA 30%; P is for PPF; and 0.1 means 0.1%. The total specimens (432 Nos.) were prepared for studying different properties, such as compressive strength, flexural strength and water absorption with ages of 7 and 28 days for M30*—M30, M35*—M35 and M40*—M40-grade concrete. For example: M30*—M30-grade concrete indicates 30% OPC replacement by fly ash and the addition of PPF at 0.0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5% six times and with six duplicates, with 36 specimens prepared and tested in each test. The corrected compressive strength results of 60 mm thick paver blocks with OPC replaced by 30% FA and addition of 0.0% to 0.5% PPF with different ages are shown. The paver blocks have been named according to their grade designation, FA replacement proportion and PPF addition.

Figure 2. Pictorial view of paver block.

For determination of dimensions, the aspect ratio and plan area of paver blocks from IS: 15658 (2006) [4] have been followed. Length of the paver block was measured at two representative positions across two opposite faces with the help of digital calliper. Four blocks of the specimen were taken to observe the mean dimension. We performed two observations per block and found their mean. Mean of the four blocks was taken as final length dimension to the nearest one mm. The width measurement of the aver block was taken at 3 distinct points and mean was found. Four blocks of the specimen were taken to observe the mean dimension. Mean was calculated using three observations per block. Mean of the four blocks was taken as final width dimension to the nearest one mm. The thickness of the paver blocks was measured at four distinct positions and the mean value was calculated. Aspect ratio was the ratio of mean length to mean thickness. Mean of the four blocks was taken as the final aspect ratio to the nearest 0.1. A desirable aspect ratio should not be more than four.

Four blocks were taken randomly for observations of the plan area. The specimen was suspended by putting it in wire basket/modified system and completely submerging it in water. The weight was recorded to the nearest 0.001 kg (*Wa*). We took the wire basket out of water, removed the specimen from the basket, and allowed coarser wire mesh to rest for one minute to drain water. We removed water with the cloth from the specimen. We weighed the specimen immediately to the nearest 0.001 kg (*Ww*). The plan area was calculated by the following equation:

$$Plan\ area = \frac{W_w - W_a}{t} \times 10^6 \quad (1)$$

where *Wa* is the weight of submerged paver block, *Ww* is the dried weight of paver block and *t* is the thickness of the specimen in mm.

2.2.2. Testing of Specimens

Cured paver blocks for different test ages were subsequently used for testing. Individual test specimens were considered for determining the strength and durability properties at different test ages as per IS: 15658 (2006) [4]. The strength (compressive and flexural) of paver blocks at 7 and 28 days was observed for specimens with and without the addition of PPF in varying proportions. The corrected compressive strength was obtained by multiplying the average compressive strength by the corresponding correction factor for the thickness following IS: 15658 (2006) [4].

The manufactured paver blocks could be used for road surfacing. The failure load was recorded to the nearest 0.1 N.

The water absorption test of paver blocks was conducted as per IS: 15658 (2006) [4]. Three randomly selected specimens were taken after curing of 28 days and completely immersed in water for 24 and 2 h. The specimens were removed from water and allowed to dry for one minute at room temperature. After saturation, the specimens were dried in a ventilated oven at 107 and 7 °C for more than 24 h. The dry weight of each specimen (*Wd*) was recorded in kg to the nearest 0.001 kg.

The compressive and flexural strengths of paver blocks are the most significant properties that have been studied for M30-, M35- and M40-grade designation paver blocks for 7 and 28 days. Compressive strength of concrete paver blocks is the most significant property as per Kumar et al. [34]. Compressive strength of paver blocks of concrete mixes with 30% replacement of OPC by fly ash and addition of PPF in an increment of 0.1% ranging from 0.0% to 0.5% at different ages was observed. Four paver block specimens were used to observe average compressive strength and to obtain corrected compressive strength. The average observed compressive strength was multiplied by a corresponding correction factor for 60 mm thickness by 1.06 and 80 mm thickness by 1.18, respectively.

3. Results and Discussion

The workability of fresh concrete is considered to be an important property to understanding its behaviour at sites in terms of flowability, compatibility and stability. Aggarwal [35] defines workability as that property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, compacted and finished. As paver blocks are manufactured with a low workability, the compaction factor test is preferred as suggested in IS: 456 and the values range from 0.75 to 0.80 for pavement. The compaction factor test reveals the behaviour of fresh concrete under the action of external forces [36]. It measures the compactness of concrete, which is an important aspect of the workability, by measuring the level of compaction achieved for a given amount of work. The compaction factor test is more accurate than the slump test for medium- to low-workability concrete [37]. The compaction factor test is more sensitive and gives more consistent results [11,14]. The results of the compaction factor test for different grades of concrete composites are given in Figure 3.

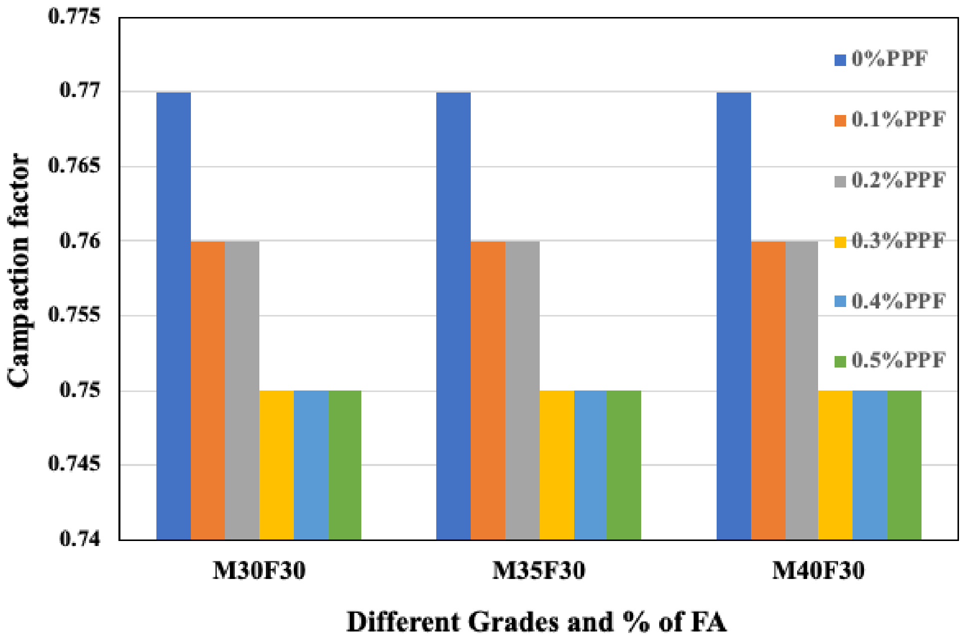

Figure 3. Comparison of compaction factors for different grades.

The result shows that the compaction factor does not change up to the inclusion of 0.2% PPF in all three of the grades under discussion. However, beyond 0.3% PPF, a decrease was observed in the value of the compaction factor for all three of the grades. The reduction in the workability with the addition of a higher volume of fibre content may be due to the amount of air trapped in the inner core of the concrete composite [38]. The results of the compaction factor test, which range between 0.75 and 0.77, meet the requirement of workability for pavements as suggested by Aggarwal [35] as well as Ramamrutham and Narayanan [39]. The mean observed length, width and thickness were 200 mm, 165 mm and 80 mm, respectively, which satisfies the tolerance limits of IS: 15658 (2006) [4]. The aspect ratio satisfies the requirement of IS: 15658 (2006) [4]. The plan area of the paver blocks was calculated and found to be 28,000 mm^2.

3.1. Effect of Paver Blocks' Thickness on Compressive and Flexural Strength

The corrected compressive strength results of 60 mm thick paver blocks with OPC replaced by 30% FA and the addition of 0.0% to 0.5% PPF at different ages are tabulated in Table 5. The paver blocks have been named according to their grade designation, FA replacement proportion and PPF addition. The corrected compressive strength at 28 days for all three of the grades increased with the addition of PPF compared to that of the corresponding nominal mixes. The maximum increase in the corrected compressive strength for 28 days was attained with 0.3% PPF and after that, the strength decreased. Additionally, after 28 days, the maximum gain in strength was observed for the lower grade, i.e., M30, and the minimum gain was observed for the highest grade, i.e., M40. It can be further concluded that the higher the grade, the higher the cement content, and hence, the lower the gain percentage after 28 days of the corrected compressive strength. It was observed that the strength of all the mixes increased with age. The strength of all three of the grades, i.e., M30, M35 and M40 paver blocks mixed with 0.3% PPF, was found to be at a maximum. Hence, 0.3% PPF can be considered as the optimum dosage. Guo et al. [40] reported that 0.25% alkaline-treated kenaf fibres reduced autogenous shrinkage more while reducing the drying shrinkage cracking on cement pastes. Additionally, the target compressive strengths for the M30, M35 and M40 grades, i.e., 34.5 N/mm^2, 39.5 N/mm^2 and 44.5 N/mm^2, respectively, were achieved at 28 days for all the mixes with varying proportions of PPF. The corrected compressive strength results of 80 mm thick paver blocks with OPC replaced by 30% FA and the addition of 0.0% to 0.5% PPF at different ages are tabulated in Table 6. The paver blocks have been named according to their grade designation, FA replacement proportion and PPF addition.

Table 5. Corrected compressive strength results of 60 mm thick M30-, M35- and M40- grade paver blocks with varying proportions of PPF.

Grade	w/c	SP	PPF	Thick	Corrected Compressive Strength [N/mm^2]	
			M30-grade paver block			
					7 Days	28 Days
M30F30P0.0	0.43	2.08	0.000	60	23.63	35.80
M30F30P0.1	0.43	2.08	0.385	60	23.80	37.50
M30F30P0.2	0.43	2.08	0.770	60	24.96	38.40
M30F30P0.3	0.43	2.08	1.155	60	25.53	39.10
M30F30P0.4	0.43	2.08	1.540	60	24.83	38.80
M30F30P0.5	0.43	2.08	1.925	60	24.60	38.40
			M35-grade paver block			
M30F30P0.0	0.43	2.11	0.000	60	27.34	40.60
M35F30P0.1	0.43	2.11	0.390	60	27.55	41.50
M35F30P0.2	0.43	2.11	0.780	60	27.66	42.10
M35F30P0.3	0.43	2.11	1.170	60	28.10	42.90
M35F30P0.4	0.43	2.11	1.560	60	26.69	42.10
M35F30P0.5	0.43	2.11	1.950	60	26.40	41.80
			M40-grade paver block			
M40F30P0.0	0.40	2.25	0.000	60	30.19	44.77
M40F30P0.1	0.40	2.25	0.418	60	30.95	45.75
M40F30P0.2	0.40	2.25	0.836	60	31.18	46.90
M40F30P0.3	0.40	2.25	1.254	60	31.21	47.29
M40F30P0.4	0.40	2.25	1.672	60	29.50	46.90
M40F30P0.5	0.40	2.25	2.090	60	29.40	46.60

Table 6. Corrected compressive strength results of 80 mm thick M30-grade paver blocks with varying proportions of PPF.

Grade	WCR	SP	PPF	Thick	Corrected Compressive Strength [N/mm^2] 7 Days	28 Days
			M30 grade			
M30F30P0.0	0.43	2.08	0.000	80	23.24	35.30
M30F30P0.1	0.43	2.08	0.385	80	23.54	37.10
M30F30P0.2	0.43	2.08	0.770	80	24.70	38.10
M30F30P0.3	0.43	2.08	1.155	80	25.50	38.70
M30F30P0.4	0.43	2.08	1.540	80	24.60	38.40
M30F30P0.5	0.43	2.08	1.925	80	24.36	38.06

Table 6. *Cont.*

Grade	WCR	SP	PPF	Thick	Corrected Compressive Strength [N/mm^2] 7 Days	28 Days
			M35 grade			
M35F30P0.0	0.43	2.11	0.000	80	26.84	40.19
M35F30P0.1	0.43	2.11	0.390	80	27.15	41.15
M35F30P0.2	0.43	2.11	0.780	80	27.60	41.90
M35F30P0.3	0.43	2.11	1.170	80	27.90	42.60
M35F30P0.4	0.43	2.11	1.560	80	26.50	41.70
M35F30P0.5	0.43	2.11	1.950	80	26.18	41.52
			M40 grade			
M40F30P0.0	0.40	2.25	0.000	80	29.92	44.57
M40F30P0.1	0.40	2.25	0.418	80	30.60	45.30
M40F30P0.2	0.40	2.25	0.836	80	30.70	46.60
M40F30P0.3	0.40	2.25	1.254	80	31.00	47.00
M40F30P0.4	0.40	2.25	1.672	80	29.36	46.60
M40F30P0.5	0.40	2.25	2.090	80	29.20	46.36

The corrected compressive strength at 28 days for all three of the grades increased with the addition of PPF compared to that of the corresponding nominal mixes. The maximum increase in the corrected compressive strength at 28 days was attained with 0.3% PPF and after that, the strength decreased. Additionally, it was observed that at 28 days, the maximum gain in strength was observed for the lower grade, i.e., M30, and the minimum was observed for the highest grade, i.e., M40. It can be further concluded that the higher the grade, the higher the cement content and hence, the lower the gain percentage at 28 days of corrected compressive strength with respect to the hydration of the concrete. This trend of the corrected compressive strength results of paver blocks agrees with that observed by Kashiyani et al. [41], who stated that the addition of polypropylene fibre improves the compressive strength of paver blocks and reported that 30% fly ash is the optimum dosage.

The strength of all the mixes increased with age. The strength of all three of the grades, i.e., M30, M35 and M40 paver block mixes with 0.3% PPF, was found to be the maximum from 28 days onwards. Hence, 0.3% PPF can be taken as the optimum dosage. Additionally, the target strengths for the M30, M35 and M40 grades, i.e., 34.5 N/mm^2, 39.5 N/mm^2 and 44.5 N/mm^2, were achieved at 28 days for all the mixes with varying proportion of PPF. The compressive strength of the paver blocks at 28 days for all three of the grades increased with the inclusion of PPF compared to that of the corresponding nominal mixes for both thicknesses. It was found that the maximum increase in the compressive strength at 28 days was attained with 0.3% PPF and after that, it decreased in both cases. It was observed that with the addition 0.3% PPF at 28 days, the compressive strength for the 60 mm thick paver blocks was higher than that for 80 mm thick paver blocks in all grades. Panizza et al. [42] observed that the mechanical and physical characterization improved during metakaolin-slag-fly ash-potassium silicate geopolymer mortar embedding in inorganic recycled aggregates. In the study by Rao et al. [14], the effect of OPC replacement by fly ash decreased the compressive strength and the effect of PPF on fly ash concrete improved concurrently.

By analysing the test results of the flexural strength for various mixes with varying proportions of PPF at various ages, it was observed that the flexural strength of all mixes increased with increases in age. The flexural strength was found to be the maximum at 0.3% PPF in all the grades and after that, it decreased. Hence, 0.3% PPF may be considered as an optimum dosage for all grades of paver blocks. The flexural strength of the mixes up to 0.5% PPF was more than that of a reference mix of 0% PPF at all ages. Hence, it is feasible to use even up to 0.5% PPF; however, the optimum dosage is 0.3% PPF, as it results in the maximum flexural strength at all ages. All the mixes at 28 days attained the target flexural strength.

The test results of the flexural strength of the paver blocks with varying percentages of PPF showed that the flexural strength at 28 days was found to be the maximum for all three of the grades at the 0.3% inclusion level of PPF. It was also observed that the strength decreased after the addition of 0.3% PPF. With the addition of different percentages of PPF for all three of the grades, the target flexural strength was attained at all the ages. It can be concluded that, from the flexural strength point of view, PPF can be safely used up to 0.5% in all grades; however, the optimum dosage is recommended as 0.3% for the maximum strength. The flexural strength of the mixes at all the ages lied between 10% and 20% of the respective compressive strength, which is in agreement with Aggarwal et al. [35].

The test results of the flexural strength of the paver blocks with varying percentages of PPF showed that the flexural strength at 28 days was found to be the maximum for all three of the grades at the 0.3% inclusion level of PPF. However, the increase in the flexural strength was observed in 0.4% PPF as well as 0.5% with age. It was also observed that the strength decreased after the addition of 0.3% PPF. With the addition of PPF in different percentages for all three of the grades, the target flexural strength was attained at all ages. It can be concluded that, from the flexural strength point of view, PPF can be safely used up to 0.5% in all grades; however, the optimum dosage is recommended as 0.3% for the maximum strength. By analysing the test results of the flexural strength for the various mixes with varying proportions of PPF at various ages, it was observed that the flexural strength of all the mixes in both thicknesses increased with the increase in age. The flexural strength was found to be the maximum with the addition of 0.3% PPF for all the mixes at 28 days. Hence, 0.3% PPF may be taken as an optimum dose for all the grades and in both thicknesses of paver blocks. The flexural strength of all the mixes with the addition of PPF was greater than that of the reference mix at all the ages. Hence, it is feasible to use even up to 0.5% PPF; however, the optimum dose is 0.3% PPF, as it gives the maximum strength at all ages. All the mixes at 28 days attained the target flexural strength.

3.2. Effect of Paver Blocks' Thickness on Water Absorption

The durability properties of precast paver blocks were tested by experimentation through the water absorption test, freeze–thaw resistance test and abrasion resistance test at 28 days in accordance with IS: 15658. The water absorption of M30-, M35- and M40-grade designation paver blocks with varying percentages of polypropylene fibre at the rate of 0.0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5% was observed for 60 mm and 80 mm thicknesses separately as per IS: 15658 (2006) [4]. Three blocks were tested at 28 days and the mean results were obtained.

The water absorption test results of M30-, M35- and M40-grade designation paver blocks with varying percentages of polypropylene fibre at the rate of 0.0%, 0.1%, 0.2%, 0.3%, 0.4% and 0.5% were analysed. At 28 days, the water absorption for the reference mix was obtained as 4.52%, 3.72% and 2.59% for the M30, M35 and M40 grades, respectively. These were within the 6% limit provided by IS: 15658 [4]. For the M30 grade with the addition of PPF from 0.1% to 0.4%, the water absorption was reduced to 3.82%, 3.15%, 2.45% and 1.28%, respectively, and for 0.5%, the water absorption increased to 1.50%. For the M35 grade with the addition of PPF from 0.1% to 0.4%, the water absorption was reduced to 2.90%, 2.74%, 2.69% and 2.16%, respectively, and for 0.5%, the water absorption increased to 2.65%. For the M40 grade with the addition of PPF from 0.1% to 0.4%, the water absorption was reduced to 2.48%, 2.28%, 2.21% and 1.35%, respectively, and for 0.5%, the water absorption increased to 1.39%. The addition of PPF in all the grades resulted in lower water absorption than that of the reference mix. This clearly indicates that the durability was improved by the addition of PPF. As all the water absorption results are within the permissible limits as per code, PPF can be safely added up to 0.5% in paver blocks. However, the optimum dosage from the water absorption point of view for 60 mm thick paver blocks was obtained as 0.4% PPF, as the water absorption is at the minimum at this proportion for all the grades.

Similar types of paver blocks were prepared by Velumani and Senthikumar [43] and they reported blending up to 35% of a sludge with a cement replacement in paver blocks.

At 28 days, the water absorption for the reference mix was obtained as 3.90%, 3.77% and 3.62% for the M30, M35 and M40 grades, respectively, within the 6% limit provided by IS: 15658 (2006) [4]. For the M30 grade with the addition of PPF from 0.1% to 0.4%, the water absorption was reduced to 2.60%, 2.43%, 2.24% and 1.41%, respectively, and for 0.5%, the water absorption increased to 1.95%. For the M35 grade with the addition of PPF from 0.1% to 0.4%, the water absorption was reduced to 3.65%, 3.47%, 2.98% and 1.76%, respectively, and for 0.5%, the water absorption increased to 2.41%. For the M40 grade with the addition of PPF from 0.1% to 0.4%, the water absorption was reduced to 3.44%, 2.78%, 2.29% and 1.44%, respectively, and for 0.5%, the water absorption increased to 1.96%. The addition of PPF in all grades resulted in a lower water absorption than that of the reference mix. This clearly indicates that the durability was improved by the addition of PPF [44–46]. A similar observation was made by Mishra et al. [36], who added marble dust into concrete. As all the results of the water absorption tests are within the permissible limits as per 24-8 the code, PPF can be safely added up to 0.5% in paver blocks. However, the optimum dosage from the water absorption point of view for 80 mm thick paver blocks is obtained as 0.4% PPF, as the water absorption is at the minimum at this proportion for all the grades [47].

3.3. Cost Effectiveness

The manufacturing costs of paver blocks with the addition of 0.3% PPF and a 30% replacement of OPC by fly ash is shown in Table 7. Based on the calculations of cost effectiveness, INR 60/- is predicted to save 20% of costs. This is useful because India is a large country with a dense rural/urban road transport network where paver blocks can find potential applications [48,49].

Table 7. Cost effectiveness.

Cost Effectiveness	
Paver blocks with 100 % OPC Manufacture of 100 pieces of paver blocks by using cement 50 kg [1 bag]. Cost of 50 kg [1 bag] of OPC = Rs 300/-	Paver blocks with OPC, fly ash, PPF composite Manufacture of 100 pieces of paver blocks by using (cement 35 kg + 15 kg fly ash + 0.125 kg PPF). Cost of 35 kg cement at 300/50 kg = Rs 210/- Cost of fly ash (waste material) = Rs 0/- Cost of PPF 0.125 kg = Rs 30/- Total cost = Rs 240/-
Saving in cost = 300−240 = Rs 60/- Percentage saving $= \left[\frac{60}{300}\right] \times 100 = 20\%$	

Shrivastava and Bajaj [15] studied high-volume fly ash concrete of M20, M50 and M70 grades and replaced the OPC with 35%, 50% and 70% fly ash; they reported that the maximum flexural strength was attained at the 35% replacement level and saved 12% of the cost. The manufacturing of paver blocks by using waste materials would help the nation because it safely disposes waste materials, has zero production value, cuts down on CO_2 emissions and at the same time improves the economy. From the above deliberation, it can be concluded that for sustainability, it is necessary to conserve raw materials by using waste materials in the manufacturing of paver blocks for environment-friendly construction [50].

4. Conclusions

The objective of the present study was to prepare a mix design for the fabrication of paver blocks of M30, M35 and M40-grade designations, replacing the OPC with 30% F type fly ash and adding PPF at weights of 0.1%, 0.2%, 0.3%, 0.4% and 0.5% of the cementitious materials. This study was carried out with the aim to evaluate the compressive and flexural strengths of paver blocks at 7 and 28 days. Since paver blocks have a potential application in road surfacing for various types of traffic loads, they were tested for their strength and durability properties. As Indian climatic conditions constantly change from hot to rainy to cold, the importance of durability was specifically deliberated. The aim of the study is to make the precast construction industry more sustainable by using by-products such as fly ash and PPF. This will not only save the energy required for cement production but will also safeguard the environment from the effects of greenhouse gases released from the cement industry. At the same time, the aggregates required for the cement industry will be conserved. On the basis of the test results of M30-, M35- and M40-grade designations of paver blocks, the following conclusions can be drawn from the present study.

Fly ash is a waste material to be used for the manufacture of paver blocks of different grades and thicknesses, whose resulting products are likely to be economical, energy-efficient and eco-friendly. OPC replaced by fly ash would generate higher profits, resulting in an overall reduction in cost by 20% at an optimal level of 0.3% PPF in all grades and thicknesses. Other waste materials, such as rice husk ash, metakoline, plastic, sludge, marble and other types of PPF, may be investigated to assess their suitability in paver blocks applications. Other statistical tools can be used for the prediction and validation of these experimental results for better understanding.

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