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TECHNICAL PAPER

Influence of recycled concrete aggregates and blended cements on the mechanical properties of pervious concrete

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Abstract

The paper presents the results of an investigation conducted to study the strength properties of pervious concrete containing coarse recycled concrete aggregates (RCA). In this study, 13 pervious concrete mixes were prepared with the use of RCA replacing coarse natural aggregates (NA) by 0, 25, 50, 75 and 100%. Keeping the water–cement (w/c) ratio constant, Viscosity Modified Agent (VMA) was added at 0.8% by weight of binder content. Being environmentally advantageous, 30% Fly Ash (FA) has been added with 70% Ordinary Portland Cement (PC) in the binder of control mix. Despite being environmentally safe product, metakaolin (MK) also tends to enhance the properties of concrete containing RCA. Therefore, keeping the PC content 70% for all mixes, FA was replaced with MK at two different levels of 5% and 10% to improve the properties of pervious concrete made with RCA. Specimens in the form of cubes, cylinders and beams were prepared for studying the mechanical properties at different ages of curing. The test results showed that there was significant loss in compressive, splitting tensile and flexural strength of pervious concrete while increasing the percentage of RCA replacing NA. Addition of 5% MK compensated the decrement noticed in the strength properties after replacement of NA with RCA. The mix with 25% RCA and 5% MK was having almost same compressive strength as that of reference mix. 10% MK further enhanced the strength properties and it was concluded that loss of compressive strength in pervious concrete due to addition of 50% RCA can be compensated by the addition of 10% MK.

Keywords Pervious concrete · Porous concrete · Mechanical properties · Supplementary cementitious materials · Recycled concrete aggregates

Introduction

The recent climate changes in the world crusade one's brain to think about the necessary infrastructural changes to deal with the untimely abysmal storm water. The researchers in the past tried to study the climate change effects on storm water infrastructures in the urban areas of Las Vegas Valley and construed that life-time systems of drainage have to be designed with maximum capacity [44]. The higher growth of urbanisation leads to the development of impervious areas. The excessive growth of impervious areas leads to lower passing of water coming from rains into the ground [38]. An amazing type of concrete, called pervious concrete, porous concrete or no fines concrete is made up of interconnected voided structure which allows the water percolation while preserving the structural performance (ACI [2] Chapter-1). Pervious concrete was first developed in 1980s in Japan for its eco-friendly advantages. Since 1980s, it has been greatly used in USA and Europe too due to the enormous environmental benefits like managing storm water run-off, restoring the groundwater and reduction of soil and water pollution [7, 8, 25, 32, 42, 46]. Pervious concrete contains binder paste and coarse aggregates with uniform or close-graded particle size distribution and also either nil or small quantity of fine aggregates [13, 30, 35]. Generally, the water permeability and porosity of the pervious concrete lie in the range of 15–30% and 1.4–12.4 mm/s, respectively (ACI [2] Chapter-1). Likewise, the compressive strength of pervious concrete is approximately 2.8–28 MPa, which is quite less than that of normal concrete (17–40 MPa) (ACI [2] Chapter-1). Despite having low compressive strength, the pervious concrete is still preferred globally having numerous environmental benefits, viz. controlling storm water run-off,

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slope stabilizations, pedestrian pathways, parking lots and light vehicular lots. In addition to this, pervious concrete is also beneficial in absorbing the acoustics, regulating heat and humidity, act as an insulator and effective barrier for the heavy metal removal from acid mine drainage [17, 43].

The enormous usage of concrete as a construction material is exponentially increasing these days, which results in increasing consumption of Coarse Natural Aggregates (NA). It has been surveyed that world's concrete consumption is annually about six billion tonnes [24]. This situation is definitely leading to take a call for preserving natural aggregate resources. Coarse Recycled Concrete Aggregates (RCA) got by sorting out the construction and demolition (C&D) waste as an alternative to NA is being used to minimise the environmental effect due to concrete construction.

However, the properties of these aggregates may be inferior to those of NA, due to the presence of comparatively compressible and porous remainder mortar on an average RCA particle [26]. This may bring up concerns about the mechanical properties of the concretes produced with RCA. This situation may also be the same in the case of pervious concrete containing RCA since the use of RCA may weaken the strength of matrix between RCA and binder paste.

There has been an extensive research on the different properties of previous concrete incorporating different kind of materials such as polymers, supplementary cementitious materials, pumice, and slag aggregates. Some of the researchers have emphasised on the usage of polymers for the production of pervious concrete to enhance its mechanical and hydrological properties [9, 37, 47]. In the last few years, several authors have encouraged the usage of RCA [6, 37, 49, 50]. The strength, fracture as well as the fatigue properties of the pervious concrete have been analysed after the addition of cement additives [12]. The strength and durability properties of pervious concretes containing Fly Ash (FA) and nanomaterial were also studied [11, 29]. It was also tried to develop a correlation among the compressive and the splitting tensile strength for the pervious concrete by replacing the cement with Ground Granulated Blast-Furnace Slag by 30% [16]. The cement was replaced by palm oil fuel ash up to 40% (by mass) in pervious concrete and it was found that compressive and tensile strength properties of the pervious concrete mixes was decreased [27]. The properties of pervious concrete were investigated using steel slag and dolomite aggregates of different sizes and proportions and it was found that properties were influenced more by the type of aggregate than the size of aggregate [14]. The properties of pervious concrete were also investigated by replacing NA with acidic pumice aggregates partially and it was found that mechanical properties of pervious concrete mixes were decreasing with increase in the replacement levels of pumice [34]. The past studies have revealed that mechanical properties of pervious concrete mixes containing RCA are always on the lower side than that of pervious concretes containing NA [37]. Coarse natural aggregates were replaced with RCA at different percentages of 20, 40, 60, 80 and 100 and it was revealed that pervious concrete with RCA up to 60% replacement level revealed quite acceptable results because of decent bonding between cement paste and RCA [49]. The pervious concrete with RCA was also prepared replacing natural aggregates by 50% and 100%; silica fume was also used to enhance the strength of pervious concrete mixtures [1]. The RCA was also incorporated in pervious concrete mixes replacing natural aggregates at different proportions 25–100%. The strength of these pervious mixes got deteriorated due to addition of RCA [18]. Viscosity Modified Agent (VMA) has also been used in previous studies to avoid segregation and to enhance the internal cohesion of pervious concrete mixes [10, 51].

Fly ash is an unburned residue which is obtained as a by-product of burning pulverised coal in any power generation plant. Chemically, when mixed with water PC, it reacts with the hydration product calcium hydroxide (CH) of PC and produce calcium–hydrate–silicate (C–S–H) and calcium–aluminate–hydrate (C–A–H) [39]. Moreover, FA has also been found to increase the workability of concrete and has been used in this investigation. Metakaolin (MK) obtained from calcining kaolin clay at high temperatures (> 700 °C) contains rich silica and aluminates. The MK improves concrete performance by packing effect and reacts chemically with undesired calcium hydroxide (CH) in the presence of water to form modified microstructure and hence improves mechanical properties and durability. The formation of secondary C–S–H by this reaction reduces total porosity and refines the pore structure, improving the strength and impermeability of the cementitious matrix [39]. Therefore, addition of MK replacing FA in a binder mix may result in the improvement of properties, as the residual CH left from the hydration reaction of FA reacts with MK and forms secondary C–S–H gels.

MK product obtained from the thermal decomposition of kaolin and without the production of CO_2 is considered to be worth replacing the cement content [45]. Addition of MK has shown enhanced strength and durability results for the other types of concretes containing up to 100% RCA [26, 33]. Self-compacting concrete had been prepared using RCA replacing NA by 25% to 100% and the earlier binder content (70% PC + 30% FA) was varied to (70% PC + 20% FA + 10% MK) to compensate the deterioration of the properties due to RCA [40]. In another study of concrete, similar binder content was varied from (70% PC + 30% FA) to (70% PC + 20% FA + 10% MK) with RCA content of 50% and probability of failure was checked by flexure fatigue testing [3].

As the manufacturing of MK is environmentally beneficial compared to PC, use of MK to enhance the properties of pervious concrete is quite expectant. Pervious concrete made from RCA has never been combined with the MK for enhancement of the properties as seen from the literature. Authors were inspired to work in the direction to determine the mechanical properties of pervious concrete containing RCA. The drop in properties of pervious concrete due to RCA could easily be enhanced or compensated by use of MK.

Significance of the study

Pervious concrete has already been investigated in the various domains with the use of different kinds of materials. Foreseeing the large availability of FA from power plants, mixing the same with PC is going to be quite beneficial for environment. Utilisation of waste concrete in the form of aggregates is also being promoted during this study. The RCA have been used as replacement of NA by 25–100%. Decrement in the mechanical properties due to addition of RCA will surely be a matter of concern. To the best of the knowledge of the authors, the study on the use of MK in pervious concrete incorporating RCA has never been done before. Besides testifying environmentally acceptable due to non-production of CO_2 while manufacturing, MK also enhances the strength properties of concrete. Therefore, current investigation was planned to analyse the mechanical properties of pervious concrete containing RCA substituting NA and an effort has been made to enhance the strength properties by addition of 5–10% MK.

Materials and methods

Materials

The primary binder used in all the pervious concrete mixes was PC of Grade-43 (conforming to IS 8112-2013), as it has been used as a standard testing material in this study according to the previously reported research [3, 26, 40, 41].

Table 1 Physical properties of the used Portland cement

Property	Portland cement (PC)
Soundness	1 mm
Specific gravity	3.15
Normal consistency	30%
Setting time	
(i) Initial	110 min
(ii) Final	270 min
Compressive strength	
7 days	35.24 MPa
28 days	47.15 MPa

To promote the reduction of carbon footprint during the production of cement and to enhance the workability, PC was mixed with FA (class-F), conforming to ASTM C618 [4], procured from Guru Gobind Singh Thermal Power Plant, Rupnagar, Punjab, India. Metakaolin (MetaCem 85C) used in this study was supplied by 20 Microns Ltd, Vadodra, Gujarat, India. Table 1 presents the physical properties of the PC and the physical and chemical properties of procured FA meanwhile MK is presented in Table 2. Laser Particle Size Analyser was used to determine the particle size distribution of PC, FA and MK, as shown in Fig. 1.

Table 3 reports the properties of NA and RCA. The RCA was obtained by crushing the waste concrete samples of minimum M25 grade available in the Concrete Laboratory of the Investigator's Institution. These concrete samples consisted of crushed rock aggregates as NA with a nominal size of 12.5 mm. The manually crushed aggregates were sorted to the adequate dimension, i.e. maximum of 12.5 mm. All the coarse aggregates used in the study, whether those are

Table 2 Physical and chemical properties of the used fly ash and metakaolin

Composition	Fly Ash (FA)	Metakaolin (MK)
SiO_2	56.50%	52.10%
Al_2O_3	17.69%	41%
Fe_2O_3	11.1%	4.32%
$CaCO_3$	–	–
CaO	3.19%	0.39%
MgO	5.4%	–
Loss of ignition	1.21%	<1%
Physical property		
Specific gravity	2.38	2.60

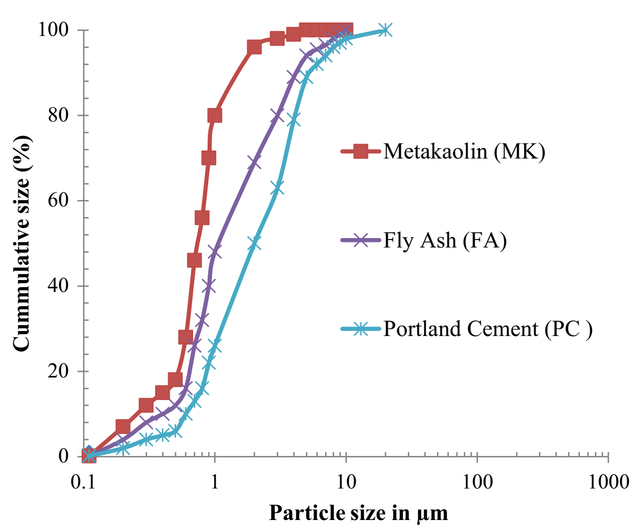

Fig. 1 Particle size distributions of PC, FA and MK

Table 3 Properties of NA and RCA used for the pervious concrete mixes

Characteristics	NA	RCA
Specific gravity	2.64	2.45
Impact value of Aggregates	16.29%	30.39%
Crushing value of Aggregates	15.78%	25.59%
Water absorption	0.69%	5.41%

NA (crushed rock aggregates) or RCA, were two different sizes of 10–12.5 mm and 4.75–10 mm, in the percentages of 25 and 75%, respectively. These size-wise specific percentages for coarse aggregates were selected after certain trials to achieve required porosity. To improve the bonding between aggregates and binder paste, Viscosity Modified Agent (VMA) named Sika Stabilizer 4R was used in all the mixes tested in this investigation. To study the impact of addition of MK in pervious concrete, the value of VMA was kept constant at 0.8% by weight of binder.

Mix proportioning and specimens

To study the strength properties, several trials were conducted first and the mix proportions were finalised. Table 4 describes the basic mix proportion used as control mix for production of pervious concrete at controlled conditions in the laboratory. The control pervious concrete used in this research was prepared using blended PC (70% PC + 30% FA) and 100% NA. Subsequently, after the addition of MK, the gross binder content of pervious concretes was altered to: (70% PC + 25% FA + 5% MK) and (70% PC + 20% FA + 10% MK).

Coarse natural aggregates and RCA, both were in saturated surface-dry condition, which was required to be attained by soaking them for time duration of 24 h before preparing the pervious concrete mixes.

The pervious concrete specimens were made ready in the concrete laboratory with the help of a tilting drum mixer. The pervious concrete samples were vibrated manually using tamping rods as per IS 1199-1959 [22] (Reaffirmed in 2004). Three types of samples were prepared: cubes of 100 mm size for compressive strength tests, 100-mm-diameter and 200-mm-high cylinders for splitting tensile strength tests and 100 × 100 × 500-mm beams for checking the flexural strength. The specimens were de-moulded 24 h after the casting. After that, all the specimens were cured in water for 7, 28 or 56 days as per the required duration of curing. Three identical samples were cast for every single test parameter and the average of obtained test results has been reported.

Table 4 Mix Proportions of control mix by weight

Binder content (kg/m^3)	Coarse natural aggregates (NA) (kg/m^3)		Water (kg/m^3)	VMA
	4.75–10 mm	10–12.5 mm		
385	1155	385	142	0.8% by weight of binder

Keeping the w/c ratio, VMA and PC content constant, the mixes were prepared using the varying percentages of FA and MK at varied percentage replacement levels of NA with RCA, as shown in Table 5. The mix proportions (by weight) of all pervious concrete mixes have also been presented in Table 6.

Testing methodology

All the specimens were tested for the permeability by constant head permeability method after 28 days of curing. With reference to ASTM D2434 [5], basic concept of constant head permeability method is to make water flow through concrete under constant pressure and measure the flow rate under steady-state flow condition. The 100-mm cube specimens were placed in the test mould and the rectangular space is filled with some sealing compound so that the flow occurred only in one direction, i.e. from top to bottom. Measurements are taken at the bottom surface after achieving the steady-state flow condition. Darcy's law was used to calculate the permeability coefficient (k) in mm/s, as per the formula written below:

$$k = QL/HAt,$$

where L is the length of specimen (mm), H is water head (mm) and A is cross-sectional area of specimen (mm^2). The

Table 5 Mix variations used in the study

Mix code	PC (%)	FA (%)	NA (%)	RCA (%)	MK (%)
100N	70	30	100	0	0
25R	70	30	75	25	0
50R	70	30	50	50	0
75R	70	30	25	75	0
100R	70	30	0	100	0
25R5MK	70	25	75	25	5
50R5MK	70	25	50	50	5
75R5MK	70	25	25	75	5
100R5MK	70	25	0	100	5
25R10MK	70	20	75	25	10
50R10MK	70	20	50	50	10
75R10MK	70	20	25	75	10
100R10MK	70	20	0	100	10

Table 6 Mix proportions of all pervious concrete mixes (by weight)

Mix code	PC (kg/m^3)	FA (kg/m^3)	MK (kg/m^3)	NA (kg/m^3)		RCA (kg/m^3)	
				4.75–10 mm	10–12.5 mm	4.75–10 mm	10–12.5 mm
100N	269.5	115.5	0	1155	385	0	0
25R	269.5	115.5	0	866.25	288.75	267.75	89.25
50R	269.5	115.5	0	577.5	192.5	535.5	178.5
75R	269.5	115.5	0	288.75	96.25	803.25	267.75
100R	269.5	115.5	0	0	0	1072.5	357.5
25R5MK	269.5	96.25	19.25	866.25	288.75	267.75	89.25
50R5MK	269.5	96.25	19.25	577.5	192.5	535.5	178.5
75R5MK	269.5	96.25	19.25	288.75	96.25	803.25	267.75
100R5MK	269.5	96.25	19.25	0	0	1072.5	357.5
25R10MK	269.5	77	38.5	866.25	288.75	267.75	89.25
50R10MK	269.5	77	38.5	577.5	192.5	535.5	178.5
75R10MK	269.5	77	38.5	288.75	96.25	803.25	267.75
100R10MK	269.5	77	38.5	0	0	1072.5	357.5

The quantity of water is 142 kg/m^3 and of VMA used is 0.8% of the total binder mix used (i.e. 0.8% of 385 kg/m^3) throughout all the mixes

time in seconds (t) required for a certain quantity of water in cubic millimetres (Q) to pass was measured. The tests for compressive strength were conducted on 100-mm cubes using a 200 T capacity universal testing machine. The load was applied at the rate of 14 N/mm^2/min approximately. Universal testing machine was also used for splitting tensile strength tests on the cylindrical samples of pervious concrete as per IS 5816 [19] at the curing age of 28 days. Standard 100 × 100 × 500-mm beam specimens, simply supported on an effective span of 450 mm and loaded at the three points were tested for flexural strength after 28 days of curing, using a 100 kN MTS digital closed-loop Servo-Controlled Actuator system. The flexural strength (f_r) of the specimen was calculated from the following expression:

$$f_r = PL_s/b_w D^2,$$

where P is the ultimate load taken by the specimen, L_s is the span length, b_w is the width of the specimen and D is the depth of the specimen.

The tests, compressive strength as well as flexural strength, were performed as per IS 516-1959 [21]. To affirm the robustness of pervious concrete, without destructing the specimens, ultrasonic pulse velocity tests were performed on cubes of 100 mm × 100 mm × 100-mm size after curing period of 28 days in accordance with IS 13311 (Part 1)-1992 [20] using an ultrasonic instrument by connecting transducers of 54 kHz on opposite sides of the cube. Although the test results of this test on pervious concrete are not much dependable, this test can testify up to some extent the characteristics of pervious concrete specimens based on the outcome of velocity values. Moreover, ultrasonic pulse velocity test may be largely effective in case of in-place pervious concrete pavements, where other destructive testing techniques are not feasible. Some of the pervious concrete mixes prepared in the laboratory are as shown in Fig. 2.

Results and discussion

Permeability

All the mixes were tested for permeability and the coefficient of permeability (k) is found to be between 6.5 and

Fig. 2 Pervious concrete specimens

9.5 mm/s confirming all the mixes as well permeable as per limits of 1.4–12.4 mm/s specified in the literature (ACI [2] Chapter 1).

Compressive strength

Trends in compressive strength of various pervious concrete mixes with replacement levels of RCA are presented in Fig. 3, which show that there is significant decrease in the compressive strength at all ages of curing. This reduction in strength due to addition of RCA in pervious concrete mixes has also been notified earlier [18].

Compressive strength of mix 25R with 25% RCA replacing NA was decreased by 4.3% at 7 days of curing with compared to 100N. This decrease in compressive strength has continued to 4.4% and 7.6% at 28 days and 56 days of curing, respectively. Mix 50R, in which NA were replaced by 50% RCA, has shown 11.9% decrement in the compressive strength after 28 days of curing with reference to control mix 100N. The reduction in strength for mix 75R (with RCA replacement level of 75%) at 7, 28 and 56 days of curing was 28.7%, 38.7% and 31.9%, respectively, compared to 100N. The mix 100R (with RCA replacement level of 100%) has shown 59.6%, 64.6% and 64.7% decrement in the compressive strengths at the curing age of 7, 28 and 56 days, respectively, compared to 100N. However, reduction in the compressive strength of the conventional concrete comprising of 100% RCA replacing NA has been reported up to 35% [28, 36, 48]. Moreover, this strength decrement trend has also been witnessed for pervious concrete after replacing NA from 25 to 100% with RCA [18]. The observed decrease in compressive strength by replacement of NA with RCA is due to the weakened properties of the latter. The additionally adhered mortar on the RCA developed weaker interfacial transition zone between the cement paste and RCA leading to the reduction in strength. The more the RCA content is increased, the decrease in strength was accelerated.

Figure 4 presents the comparison of compressive strengths for control pervious concrete and pervious concrete incorporating RCA and 5% MK in each mix. In general, compressive strengths of the pervious concrete mixes prepared with RCA were enhanced with the addition of MK. This phenomenon has already been observed in conventional concretes [31]. The comparison reveals that adding MK in the mix with 25% RCA increases the compressive strength by 6.2% in the curing age of 28 days. Similarly, 5% MK addition in the mixes with 50%, 75% and 100% RCA increased the compressive strengths by 9.8%, 7.3% and 8.8%, respectively. This enhancement in strength due to the addition of MK in pervious concrete mixes may be imputed to the fact that pozzolanic reaction improved the cement paste matrix. Metakaolin being a finer element is also playing the role of filler and improving the RCA pervious concrete. These observations have also been observed with some other kind of cementitious materials used in pervious concretes [1]. When compared to the reference mix 100N, the compressive strengths of mixes 25R5MK, 50R5MK and 100R5MK were still inferior to the extent of 3.2%, 33.6% and 61.5%, respectively, at the curing age of 28 days. The mix 25R5MK showed a better compressive strength (around 1.5%) than the reference mix. This means that the loss in the strength by adding of RCA was compensated by addition of 5% MK.

Addition of MK up to 10% by partially replacing FA in the binder content further increased the compressive strength of mixes containing RCA. The mix 25RCA10MK has shown

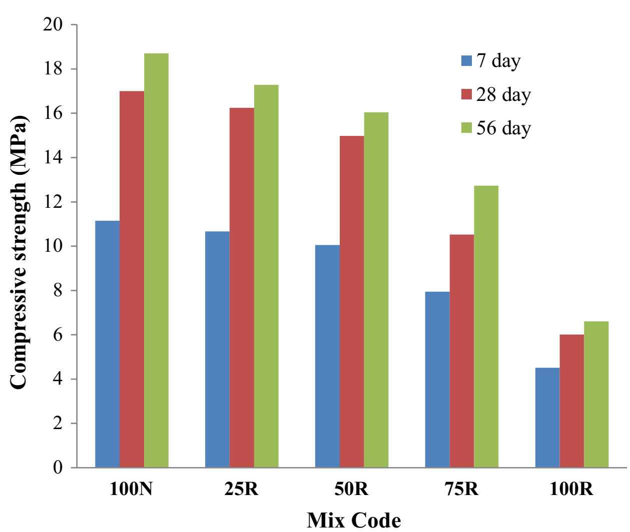

Fig. 3 Effect of RCA on compressive strength of pervious concrete

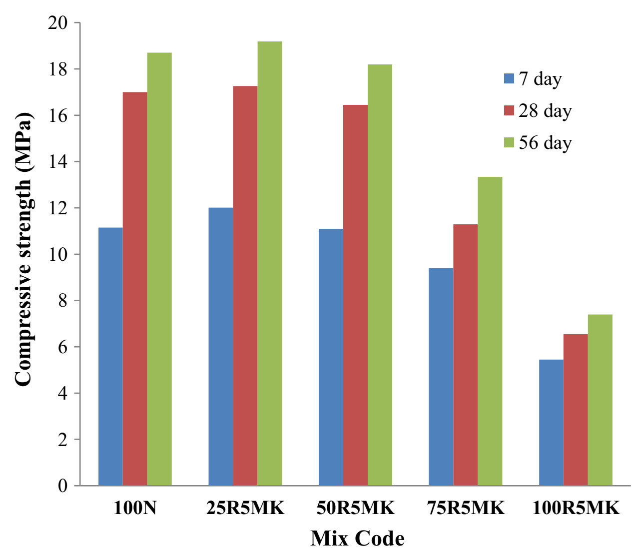

Fig. 4 Effect of 5% MK on compressive strength of pervious concrete containing RCA

2.4% better compressive strength than mix 25RCA5MK. Similarly, the mixes with 50%, 75% and 100% RCA and 10% MK have shown 3.7%, 10.1% and 12.2% increment in the strength as compared to the similar mixes with 5% MK. Increase in percentage of MK is ultimately enhancing the compressive strength properties of the pervious concrete mixes, which is also true for conventional concretes [31]. Further as depicted in Fig. 5, the mixes with 25%, 75% and 100% RCA and 10% MK have shown a reduction in the compressive strength when it was compared to the reference mix 100N. The mix 25R10MK has been showing enhanced results than reference mix 100N, almost an increment of 3.9% at the curing age of 28 days. Thus, addition of 10% MK in the mixes with 25% RCA not only compensated the loss of strength but also heightened the compressive strength value. The mix 50R10MK equalised the strength levels of reference mix 100N at the curing age of 28 days and almost same compressive strength is acquired. Table 7 presents the comparative percentage variations in compressive strength of all the mixes at 28 days of curing compared to reference mix 100N. Pervious concretes containing RCA at 50% and 100% proportions also exhibited enhancement in strength due to addition of silica fume [1]. This phenomenon of compensating the strength loss due to addition of 25% RCA with 10% MK has also been followed in some other types of concretes as well [40]. The addition of 10% MK in 50% RCA mixes compensated the loss of strength and levelled the strengths with 100N, reference mix. For the purpose of designing parking lots, pavements for drainage and other porous concrete products, the compressive strength should be ranging from 10 to 13 MPa. In case of pedestrian walkways, the lower compressive strength is quite acceptable because there will not be any kind of loading due to vehicles [23]. Therefore, the RCA mixes developed except the mixes containing 100% RCA can be utilised for constructing the pedestrian walkways.

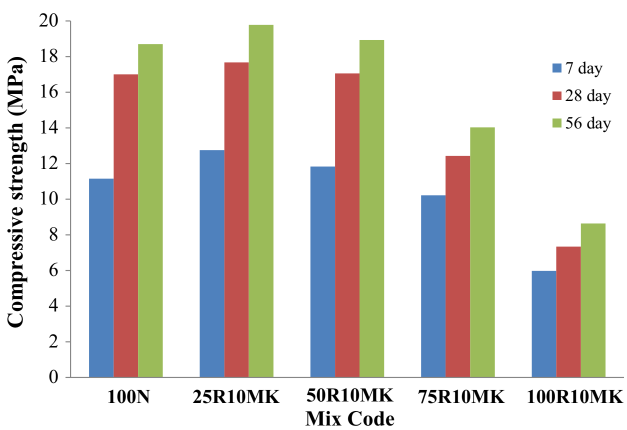

Fig. 5 Effect of 10% MK on compressive strength of pervious concrete containing RCA

Splitting tensile strength

The effect of replacement of RCA on the splitting tensile strength is shown in Fig. 6. It has observed from the plot that splitting tensile strength following the similar trend as followed by compressive strength results in above section, where the gradual increment in RCA content reduced the strength of RCA mixes. The splitting tensile strength value of mix 100N with no RCA has also been marked in Fig. 6.

In general, the splitting tensile strength of various mixes at the 28 days curing decreases due to the addition of RCA

Table 7 Comparative results of compressive, splitting tensile and flexural strength at 28 days of curing

Mix code	Compressive strength (MPa) and percentage variation from the reference mix 100N (±%)	Splitting tensile strength (MPa) and percentage (±%) variations of the mixes with MK compared to corresponding mixes with same RCA and without MK	Flexural strength (MPa) and percentage (±%) variations of the mixes with MK compared to corresponding mixes with same RCA and without MK
100N	17.00	2.24	1.950
25R	16.25 (−4.4%)	1.83	1.670
50R	14.98 (−11.9%)	1.64	1.525
75R	10.52 (−38.1)	1.39	1.348
100R	6.01 (−64.6%)	0.79	0.732
25R5MK	17.26 (+1.5%)	1.95 (+6.6%)	1.79 (+7.2%)
50R5MK	16.45 (−3.2%)	1.82 (+11.0%)	1.686 (+10.6)
75R5MK	11.29 (−33.6%)	1.445 (+4.0%)	1.397 (+3.6)
100R5MK	6.54 (−61.5%)	0.89 (+12.7%)	0.78 (+6.6)
25R10MK	17.67 (+3.9%)	2.38 (+30.1%)	1.932 (+15.7%)
50R10MK	17.06 (+0.4%)	2.08 (+26.8%)	1.821 (+19.4%)
75R10MK	12.43 (−26.9%)	1.78 (+28.1%)	1.609 (+19.4%)
100R10MK	7.34 (−56.8%)	1.034 (+30.9%)	0.791 (+8.1%)

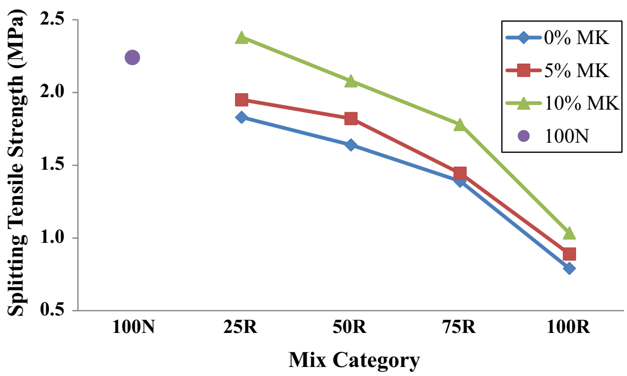

Fig. 6 Effect of MK on the splitting tensile strength of pervious concrete mixes containing RCA

in pervious concrete mixes. This reduction in splitting tensile strength, when it was compared with reference mix, was of the order of 18.3%, 26.8%, 37.9% and 64.7% for the mixes containing RCA in the proportion of 25, 50, 75 and 100%, respectively. This decrease was found quite constant in nature and has also been supported with the facts in the case of compressive strength of pervious concrete.

Mixes 25R5MK, 50R5MK, 75R5MK and 100R5MK also showed decrease in splitting tensile strength of the order of 12.9%, 18.7%, 35.5% and 60.3%, respectively, when compared with the reference mix 100N. This decrement percentage in splitting tensile strength was lower than that of mixes with 0% MK.

Further, after the addition of 10% MK, there was an enhancement in the splitting tensile strength of mix 25R10MK to 6.2%, when compared with the control mix 100N. The mix 50R10MK, when compared with control mix 100N, has shown comparable splitting tensile strength with a minor percentage decrease of 7.1%. The mixes 75R10MK and 100R10MK were showing a decrease of 20.5% and 53.8%, respectively, compared to mix 100N.

It is quite clear from the results that only 25R10MK mix with 25% RCA and 10% MK is showing little better results than the reference mix 100N. The mix 50R10MK with 50% RCA and 10% MK is having comparable splitting tensile strength with minor decrement when compared with control mix 100N.

This is attributed to the fact that partial replacement of FA, in the binder, with 5% and 10% MK in the RCA pervious concrete enhances the binder matrix bonding with the aggregates and ultimately the splitting tensile strength.

The comparison of splitting tensile strengths of RCA incorporated pervious concrete mixes with 0%, 5% and 10% MK is shown in Fig. 6. The splitting tensile strength of pervious concrete with 25% RCA got an increase of 6.6% after the addition of 5% MK compared to mix 25R. In a similar manner, after the addition of 10% MK, the increase in splitting tensile strength was 30.1% for the mixes containing 25% RCA, when compared to the mix 25R with no MK. Mixes with 50%, 75% and 100% RCA were also showing significant improvements in the strength of 11.0%, 4.0% and 12.7%, respectively, in the splitting tensile strength values after the addition of 5% MK and an increase of 26.8%, 28.1%, and 30.9% after the addition of 10% MK when compared with the corresponding mixes with 0% MK. The increase in splitting tensile strength of mixes containing MK at 28 days of curing has also been given in Table 7 compared to the corresponding mixes of same RCA content. The decrease in splitting tensile strength after the addition of RCA in pervious concrete got compensated after the addition of MK, also elaborated in the past studies [40].

Flexural strength

In case of flexural strength for pervious concrete mixes, gradual reduction in the strength has noticed after the replacement of NA with RCA, in comparison to the control mix 100N. This decrease in flexural strength for mixes 25R, 50R, 75R and 100R was of the order of 14.4%, 21.8%, 30.9% and 62.5%, respectively. This empiricism in this case has also been explained with the justifications in the preceding sections of this study with similar attributions. The decrease in the flexural strength for the mixes with 5% MK was a little lower than the mixes with no MK content. The pervious concrete mixes having 25%, 50%, 75% and 100% RCA have shown 8.2%, 13.5%, 28.4% and 60% decrement in the flexural strength after the addition of 5% MK, when compared with the control mix 100N. After the addition of 10% MK, mixes 75R10MK and 100R10MK were having 17.5% and 59.4% lower flexural strengths than the reference mix. The mix 25R10MK has shown almost same flexural strength as that of 100N. This means that after the addition of 10% MK, the reduction in strength owing to addition of 25% RCA got fully compensated. The similar results were got in the case of mix with 50% RCA, in which, after the addition of 10% MK, there was a slight difference of strength between 100N and 50R10MK. In general, the enhancement in the flexural strength after addition of 5% MK is attributed to the fact that addition of MK acts as a filler material and improves the paste matrix leading to strong interfacial transition zone.

Figure 7 depicts that flexural strengths for RCA pervious concretes with 25%, 50% 75% and 100% RCA content has enhanced by 7.2%, 10.6%, 3.6% and 6.6%, respectively, after addition of 5% MK. The increase in flexural strength continued after the increase in quantity of MK from 5% to 10%. This increase in flexural strength for 25R10MK, 50R10MK, 75R10MK and 100R10MK was of the order of 15.7%, 19.4%, 19.4% and 8.1% when compared with the similar mixes having 0% MK content. Table 7 is showing the magnitudes and comparison of flexural strengths of

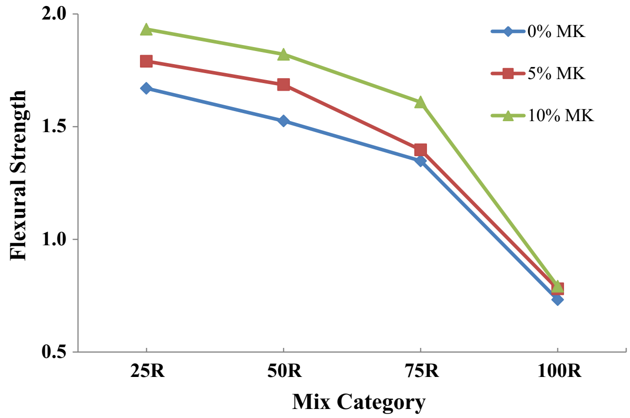

Fig. 7 Effect of MK on the flexural strength of pervious concrete mixes containing RCA

mixes containing MK (5% and 10%) with corresponding mixes containing 0% MK. The enhancement in the flexural strength due to 10% addition of MK leads to the optimum usage value of MK in the RCA pervious concrete. The reason of enhancement in strength is also supported by the earlier studies on supplementary cementitious materials [40].

Ultrasonic pulse velocity

The outcomes for this experiment for the various mixes are presented in Table 8. As shown in Table 8, the ultrasonic pulse velocity of mixes with only RCA gradually decreases after the addition of RCA substituting NA. After the addition of 5% MK, the ultrasonic pulse velocity of the mix with 25% RCA was quite close to the value for the control mix. The ultrasonic pulse velocity results for 10% MK mixes have shown improvement than the mixes with 5% MK. The mix 25R10MK has shown better results than the reference mix 100N. In general, the values for ultrasonic pulse velocity for all the pervious concrete mixes displayed a 'GOOD' concrete quality as per the grading specified in the IS 13311 (Part-1)-1992 [20].

Compressive strength vs splitting tensile strength

Figure 8 presents relation between compressive and splitting tensile strength results for different pervious concrete mixes. The correlation coefficient (R^2 value) 0.9137 reveals the relation between the two parameters is quite significant. Compressive strength test results for the various pervious concrete specimens are nearly showing similar trends as shown by the splitting tensile strength test results. Past studies also support such relationship between compressive and splitting tensile strength [23]. A linear relationship between the two parameters is also drawn, using which the prediction of splitting tensile strength may easily be done in future hypothetically.

Compressive strength vs flexural strength

Figure 9 depicts the correlation between compressive and flexural strength results for different pervious concrete mixes. The R^2 value 0.9364 depicts quite comfortable interdependency of the two strength properties. However, these results are slightly better and lucid than the earlier results from literature [23]. A linear relationship in the form of a

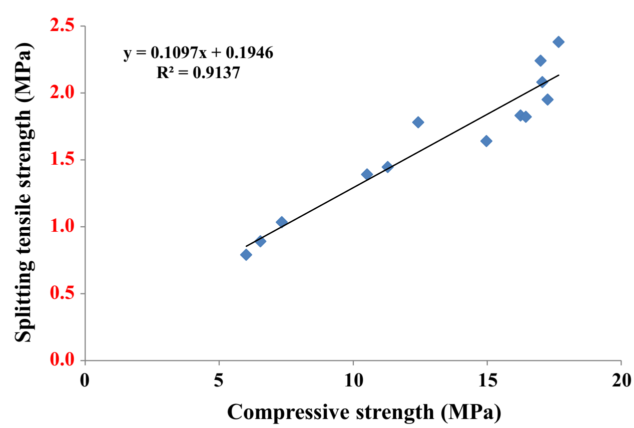

Fig. 8 Compressive strength vs splitting tensile strength of pervious concrete mixes

Table 8 Ultrasonic pulse velocity of categorised mixes

Mixes with RCA only		Mixes with RCA & 5% MK		Mixes with RCA & 10% MK	
Mix notation	28-Day ultrasonic pulse velocity (m/s)	Mix notation	28-Day ultrasonic pulse velocity (m/s)	Mix notation	28-Day ultrasonic pulse velocity (m/s)
100N	4119	100 N	4119	100 N	4119
25R	4098	25R5MK	4105	25R10MK	4176
50R	4016	50R5MK	4052	50R10MK	4064
75R	3861	75R5MK	3892	75R10MK	3934
100R	3636	100R5MK	3673	100R10MK	3701

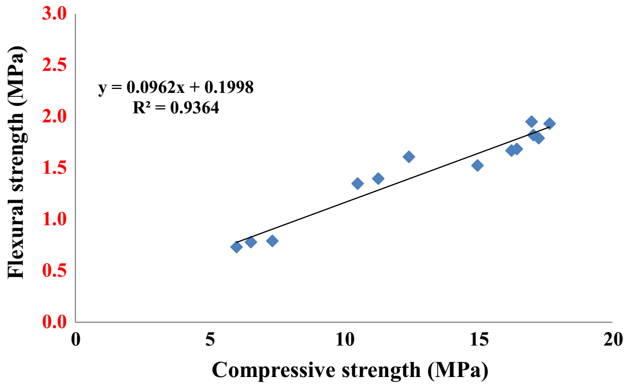

Fig. 9 Compressive strength vs flexural strength of pervious concrete mixes

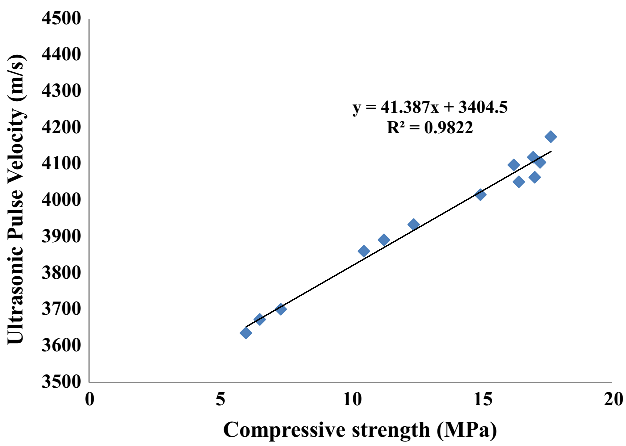

Fig. 10 Ultrasonic pulse velocity vs compressive strength of pervious concrete mixes

linear equation is also provided to predict one parameter with the help of other parameter results.

Ultrasonic pulse velocity vs compressive strength

The relationship between the ultrasonic pulse velocity and compressive strength of the pervious concrete samples is linear with R^2 of 0.9822. The R^2 value for such relationship had also been discussed in earlier researches [15], which is quite similar to the results presented in this study. The prediction of compressive strength is quite possible through this technique using the linear equation shown in Fig. 10.

Conclusions

The pervious concrete mixes manufactured with the addition of RCA by replacing NA partially or fully were successful in recycling the waste aggregates again in the concrete with acceptable quality. The idea of providing pervious strata for infrastructural developments in the form of pervious concrete pedestrians, parking lots, etc. will be quite fruitful, economical and sustainable with the combined use of RCA and blended cements. Conclusions drawn after the extensive experimental research are as below:

1. All pervious concrete mixes were found to be well permeable with coefficient of permeability ranging between 6.5 and 9.5 mm/s.
2. The addition of RCA replacing NA at different percentages reduced the compressive strength for various pervious concrete mixes. The minimum and the maximum variation in the compressive strength of about 4.4% and 64.6% has been observed for mixes containing 25% and 100% RCA, respectively, at the curing age of 28 days with compared to reference mix.
3. The inclusion of MK by 5% in the RCA pervious concrete mixes compensated the strength losses due to addition of RCA. The mix 25R5MK had the compressive strength very much analogous to the control mix 100N. This was due to the reason that MK compensated the strength loss in pervious concrete mixes due to addition of RCA. This enhancement in the compressive strength due to the addition of 5% MK was seen in every mix for 25–100% replacement level of RCA.
4. The increase in percentage for adding MK to 10% further enhanced the compressive strengths. The mix 25RMK10 had the maximum compressive strength across all the pervious concrete mixes, which was about 4% higher than the reference mix 100N.
5. For splitting tensile strength results; in case of RCA pervious concrete mixes, there were successive enhancements of strength after addition of 5 and 10% MK. Pervious concrete mixes with 25% RCA were showing the best results, before and after addition of MK. The splitting tensile strength of 25R5MK and 25R10MK got increments of 6.6 and 30.1%, respectively, when compared to 25R. Mix 25R10MK had the best splitting tensile strength, which was 6.2% better as compared to mix 100N.
6. The flexural strength results exhibited similar trends as of splitting tensile strength results. The flexural strengths of RCA pervious concrete mixes got an increment, when 5% and 10% MK was added after replacing FA from the binder mix partially. Mixes with 25% RCA were showing significantly good results as compared to other RCA mixes. The mix 25R10MK had the similar flexural strength when it was compared to reference mix 100N.
7. All the pervious concrete mixes exhibited good quality grading of concrete as per the ultrasonic pulse velocity results and these results were found to be concurrent

when compared with the compressive strength results obtained.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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