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# Roller compacted concrete pavements reinforced with steel and polypropylene fibers

Morteza Madhkhan*[1], Rasool Azizkhani[1a] and Mohammad E. Torki[2b]

[1]*Department of Civil Engineering, Isfahan University of Technology (IUT), Islamic Republic of Iran*
[2]*Department of Civil Engineering, Sharif University of Technology (SUT), Islamic Republic of Iran*

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**Abstract.** In this paper, the effects of both pozzolans and (steel and poly-propylene) fibers on the mechanical properties of roller compacted concrete are studied. Specimens for the experiments were made using a soil-based approach; thus, the Kango's vibration hammer was used for compaction. The tests in the first stage were carried out to determine the optimal moisture requirements for mix designs using cubic 150 × 150 × 150 mm specimens. In the tests of the second stage, the mechanical behaviors of the main specimens made using the optimal moisture obtained in the previous stage were evaluated using 28, 90, and 210 day cubic specimens. The mechanical properties of RCC pavements were evaluated using a soil-based compaction method and the optimum moisture content obtained from the pertaining experiments, and by adding different percentages of Iranian pozzolans as well as different amounts of steel fibers, each one accompanied by 0.1% of poly-propylene fibers. Using pozzolans, maximum increase in compressive strength was observed to occur between 28 and 90 days of age, rupture modulus was found to decrease, but toughness indices did not change considerably. The influence of steel fibers on compressive strength was often more significant than that of PP fibers, but neither steel nor PP fibers did contribute to increase in the rupture modulus independently. Also, the toughness indices increased when steel fibers were used.

**Keywords:** roller compacted concrete (RCC) pavement; steel/polypropylene fibers; pozzolans; compressive/flexural strength; toughness

## 1. Introduction

Roller compacted concrete, so called because rollers are used in the compaction of the concrete, may be defined as a no-slump concrete capable of supporting the compacting roller weight before cement setting (ACI 207.5R-99 2004). The techniques used in constructing RCC structures are similar to those employed in paving most commonly-used roads (USACE 1995). Although the use of roller compacted concrete (RCC) has been, to a large extent, limited to voluminous concrete works, e.g. dams, its advantages such as the ability to gain high compressive strength particularly at lower concrete ages, reduced paving costs, and higher construction paces have encouraged many

*Corresponding author, Assistant Professor, E-mail: madhkhan@cc.iut.ac.ir
[a]MSc, E-mail: r_azizkhany@yahoo.com
[b]Msc Student, E-mail: mohamad_torky@yahoo.com

engineers to use this type of concrete for constructing pavements.

The ingredients of RCCs are identical to those of ordinary concrete. However, after mixing and shedding the layers, a very strong consolidated surface will be produced which is appropriate for use in pavements (PCA 2005). The most important and common uses of RCC are in factories, gas stations, airports and roads where the pavement is exposed to dynamic loads or where the traffic is low but the vehicles are very heavy as in heavy-industry factories (Delatte *et al.* 2003). RCC was suggested by Qasravi *et al.* (2004) as a substitute for asphalt-concrete pavements under scorching climates in the Middle East to combat the problem of cracking under great pressures. They gathered that cement, as the chief element, influenced the tensile strength in terms of *W/C* ratio so that the tensile strength first increased at an optimum ratio and then decreased afterwards. They expressed the tensile strength versus the cement content as a simple linear function (Qasravi 2004).

Using a soil-based approach, a special method was put forward by Choi and Groom (2001) for RCC mix proportions, which is useful for small to medium-sized highway projects.

Several factors influence the mechanical properties of RCCs and many researchers have studied these factors. The effect of fly ash, as a pozzolan, on the physical and mechanical properties of concrete was investigated by Atis (2004). They figured out that fly ash enhances the strength and shrinkage of concrete as well as the hydration heat, permeability and porosity. Effects of two cementitious materials, silica-fume and pumice, on workability and the frost and compressive strengths of low-cement RCC were studied by Vahedifard *et al.* (2010). Their results revealed that silica-fume increases both the frost and compressive strengths while pumice reduces both. However, silica-fume decreases workability while pumice heightens it. The contribution of siderite fines on the compressive strength of RCC, as a cement replacement, was studied by Zdiri *et al.* (2010). They gathered from their results that within the replacement ratio of 10%, siderite fines contribute to 1.3 times the compressive strength of RCC with full cement proportioning. The effects of two distinct types of steel fibers on RCC pavements were studied by Nanni and Johari (1989). They concluded that the effects of fibers on compressive strength and elasticity modulus were beyond expectation. Even after initial cracks, tensile and flexural strengths significantly increased as a result of adding fibers. Also, fibers contributed to the better ductility of concrete.

Although numerous studies have been worked out concerning mix design of RCC, to the authors' knowledge, efficient mix designs putting to work different factors such as the simultaneous effects of fibers and pozzolans in mixtures with optimum moisture content is meager. In the present paper, a soil-based compaction methodology contributing to the optimum moisture content is used for the compaction of specimens. The behavior of RCC pavements is similar to that of slabs on the ground. While the main objective of fibers is to increase resistance against dynamic loads, the *mechanical properties*, especially compressive strength and rupture modulus, are needed for the proper *design* of such pavements under traffic loads as conformance to design codes is required. Also, for constructing these pavements, an optimum mix design needs to be obtained. Thus, this work aims to determine optimal mix proportions, and second, to investigate a number of factors including the effects of pozzolans, steel, and PPF fibers as well as the simultaneous effects of fibers and pozzolans (in mixtures with optimum moisture content) on the mechanical properties of RCCs. The properties under study include compressive strength, rupture modulus, and toughness indices. Adding fibers induced significant enhancement in concrete's compressive, tensile, and flexural strengths and its resistance against load impacts.

## 2. Materials

Choosing the ingredients is directly affected by design compressive strength, required durability, and pavement usage (ACI 325.10R-99 2004). In this research, materials include aggregates, cementitious materials (containing cement and pozzolans), water, workability agents, and fibers (containing steel and poly-propylene fibers).

### *2.1 Coarse and fine aggregates*

Raising the Nominal Maximum Size Aggregate (N.M.S.A.) causes the inter-aggregate spaces to decrease in size; therefore, the cement mortar content in the mix design decreases, leading to reduced fraction potential due to thermal stresses caused by cement hydration. That's why the N.M.S.A. is recommended to be no greater than 19 mm. In this research, crushed lime stones with an N.M.S.A. of 19 mm were used as coarse aggregates suitable for 150 × 150 × 150 mm cubic specimens and 350 × 100 × 100 mm prismatic ones. This is because 5 times the N.M.S.A. ought to be smaller than the minimum mold dimension. The grading results for the gravel and sand used in the specimens are shown in Figs. 1 and 2, respectively (according to ASTM C33). The ranges put forward by ACI 211.3R.02 persuaded the authors to choose a composition of 60 percent sand and 40 percent gravel, which conforms well to the recommended limits. The grading diagram is shown in Fig. 3.

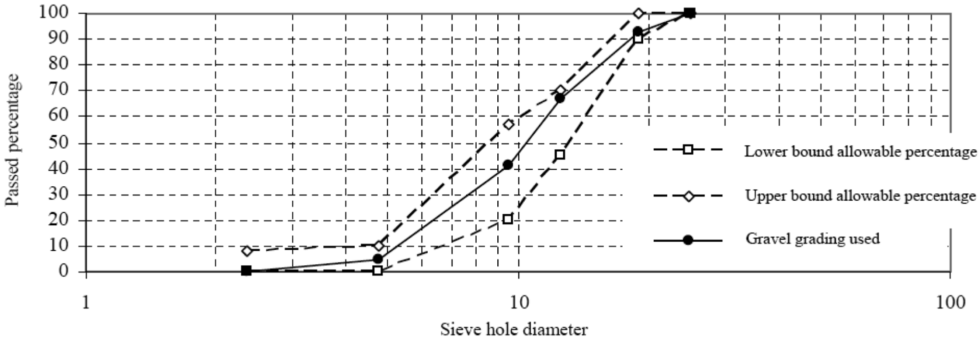


Fig. 1 Gravel grading diagram

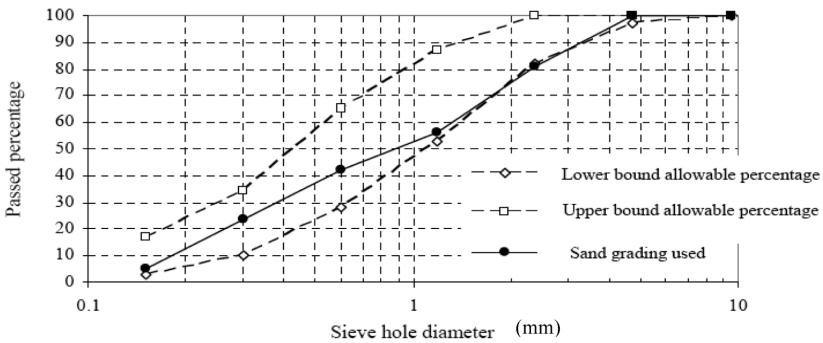


Fig. 2 Sand grading diagram

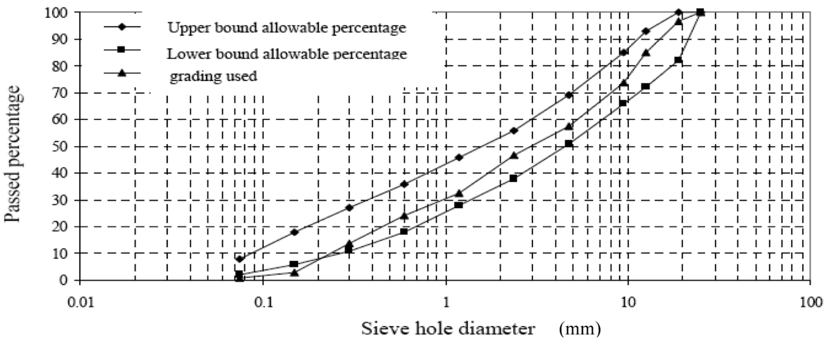


Fig. 3 Sand-gravel mix design grading

## 2.2 Cementitious materials

The cementitious materials used in RCC can be Portland cement or blended hydraulic cement, ground granulated blast furnace slag, natural pozzolans (known as Pozzolans or N-class in ASTMC618), or artificial pozzolans (known as Fly Ashes) (Hansen and Reinhard 1991). Pozzolans are basically used to reduce hydration heat and intergranular porosity (Dawis *et al.* 1937, Philleo 1967, Cabrera 1985). Moreover, not only do pozzolans raise long-term strengths of concrete, i.e. from 180 days onwards, but they also enlarge the mortar volume in fresh concrete, thus increasing the concrete compaction capability (ACI 211.3R-02 2004). Experiments performed on the properties of Taftan's pozzolans have demonstrated the admissibility of their usage in mix designs (Ghazimoradi and Ramezanianpoor 1992).

The cement used in our mix designs was Type (I) Portland cement produced at Isfahan Cement Co. The properties of this cement are given in Table 1 (Isfahan cement factory 1997). The abbreviations $f_{cement,3}$, $f_{cement,7}$, and $f_{cement,28}$ stand for the 3, 7, and 28-day compressive strengths of the cement mortar. According to the 12-16% range suitable for RCC pavements, 13% was taken for the cementitious material content so as to study the effect of pozzolans on RCC behavior. Three different contents, i.e., 0, 15, and 30 percent of cementitious materials, were allocated to pozzolans in each design.

## 2.3 Water

The water used in RCC mix designs was drinking water, which is also used in ordinary concrete. It is of consequence to note that in RCC mix designs, the water content ought to be limited so that the workability (slump) of the fresh concrete is close to zero. Therefore, according to ASTMD 558,

Table 1 Cement properties

| Mechanical properties | Compressive strength (N/mm$^2$) | | | $\frac{f'_{cement,3}}{f'_{cement,7}}$ | $\frac{f'_{cement,7}}{f'_{cement,28}}$ |
|---|---|---|---|---|---|
| | $f'_{cement,3}$ | $f'_{cement,7}$ | $f'_{cement,28}$ | | |
| Least recommended by ASTM | 12 | 19 | 28 | 0.63 | 0.68 |
| Used cement | 17 | 23 | 39 | 0.74 | 0.59 |

Table 2 Pozzolanes' properties

| Ingredients | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $Na_2O$ | $K_2O$ | $SiO_2+Al_2O_3+Fe_2O_3$ |
|---|---|---|---|---|---|---|---|---|---|
| Percentage existing in Taftan's pozzolan | 56-59 | 17-19 | 5 | 5-7 | 1.2-2 | 1.7-3 | 3.5 | 1.3-2 | 78-83 |

such mix designs had better be approached as soil-cement compositions rather than ordinary concrete mixtures (Qasravi 2004).

### 2.4 Pozzolans

The pozzolan used in our research was the natural pozzolan extracted from Taftan, the ingredients of which are given in Table 2 in conformity with ASTM C618. Studies have demonstrated that Taftan's pozzolans can be used up to 30 percent of Portland Type I or II cement content as a replacement for cement on the condition that the fineness index based on # 200 is not smaller than 95%, and its special surface area ranges between 34000 to 35000 $mm^2$/gr.

### 2.5 Fibers

In order to assess the effect of fibers on the flexural strength and the ductility of concrete, steel and poly-propylene fibers were used in our specimens. The steel fibers used were double hooked-

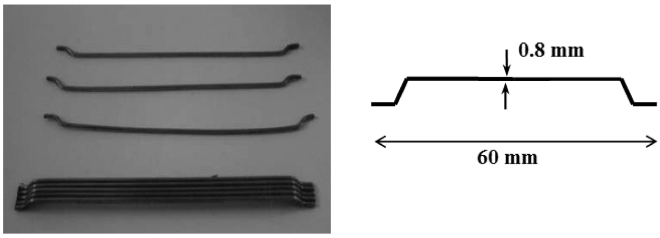


Fig. 4 Steel fibers' geometry (1*in* = 0.0254 m, 1*m* = $10^3$ mm)

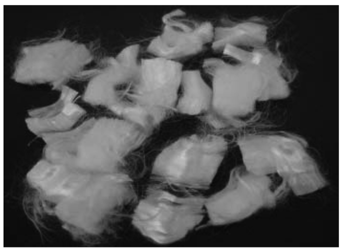

Fig. 5 Poly-propylene (PPF) fibers

Table 3 Steel fibers' properties

| Length (mm) | Diameter (mm) | Length to width ratio (aspect ratio) | Tensile strength ($N/mm^2$) | Specific volumetric mass ($kg/m^3$) |
|---|---|---|---|---|
| 60 | 0.8 | 75 | 1000 | 7800 |

Table 4 Poly-propylene fiber properties

| Color | Special weight (kg/m$^3$) | Least diameter ($\mu$m) | Tensile strength (N/mm$^2$) | Melting temperature ($^o$C) | Temperature conducting ability | Electrical conducting ability | Resistance to acids, alkalis, and salts |
|---|---|---|---|---|---|---|---|
| White | 910 | 23 | 408 | 160-165 | Limited | Limited | High |

end steel rods, shown in Fig. 4, with the properties presented in Table 3. The poly-propylene (PPF) fibers (Fig. 5 and Table 4) are produced by Bonyad Plant. As the length of this fiber must be at least 1-1.2 times the N.M.S.A, thus 19 mm long fibers were used in the specimens.

To evaluate the effects of fibers on the compressive and flexural strengths of RCC, three levels of fiber content, 30, 45, and 60 kg/m$^3$, were used for steel fibers, and one, i.e., 1 kg/m$^3$, for poly-propylene fibers. In other words, 0.4%, 0.6%, and 0.8% steel fibers together with 0.1% PPF fibers were used in the relevant designs.

### *2.6 Admixtures*

Since the presence of steel fibers reduces concrete workability and regarding the fact that RCC workability is itself very limited, workability agents were also used in steel-fiber containing mix designs. The workability agent used was SF800 whose properties fully conformed to ASTM C494. This agent helps workability to increase but water content to reduce in mix designs. The allowable content for this material is 1 to 3 percent of the total cementitious material content. In the absence of standard criteria to determine the content of workability agents needed in each mix design, a method similar to that used for obtaining optimum moisture ratios was adopted. The final mix designs and proportions are shown in Table 5.

## 3. Final mix proportions

Investigators have put forward different viewpoints concerning RCC mix designs. Fundamentally, the difference between ordinary concrete and RCC mix designs stems from the low consistency and use of unusual grading in RCC (ACI 211.3R-02 2004). Two competing approaches to RCC mix designs, namely the concrete workability determination method which is a concrete-based approach and the soil-compaction method which is a soil-based approach, are typically used for determining mix proportions. The former approach is currently used mostly in RCC dams, while the second has been particularly developed for RCC pavements of roads and is limited to mix designs with a maximum N.M.S.A of 19 mm (ACI 325.10R-99 2004).

Mix designs in the present study are determined using the soil-based approach. Since access to rollers is denied in laboratories, compaction of specimens was accomplished by means of the Kango's vibrating hammer, 750W power, which exerts 2750 impacts per minute. The hammer has a 4600 mm height and a mass of 7.5 kg. The rectangular 110 × 140 mm percussion heads were used for making optimum-moisture and compressive specimens, and 90 × 140 mm heads were used for flexural specimens. In this way, the compaction made by onsite rollers was satisfactorily simulated.

Table 5 Final mix designs and proportions

| Mix design code | Maximum mean specific gravity due to quadratic formulation, correlation factor | Optimum water dosage (%) due to quadratic formulation | Superplasticizers' weight percentage in relation to cementitious materials | Fiber contents (kg/m$^3$) | | Cementitious Materials | | | | | Aggregates | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Steel fibers | Polypropylene fibers | Cementitious to aggregate content ratio (kg/m$^3$) | Total cementitious materials (kg/m$^3$) | Pozzolanic to cementitious materials ratio | Cementitious material content: Cement (kg/m$^3$) | Cementitious material content: Pozzolans (kg/m$^3$) | Gravel to sand weight ratio | Aggregates' contents: Gravel (kg/m$^3$) | Aggregates' contents: Cement (kg/m$^3$) |
| *NF-P0* | 2.480,0.898 | 5.504 | 0 | 0 | 0 | | | | | | | | |
| *SF30-P0* | 2.487,0.762 | 5.356 | 2 | 30 | 0 | | | | | | | | |
| *SF45-P0* | 2.358,0.887 | 6.032 | 2.5 | 45 | 0 | | | 0 | 274 | 0 | | | |
| *SF60-P0* | 2.500,1.000 | 5.511 | 3 | 60 | 0 | | | | | | | | |
| *PPF-P0* | 2.427,0.955 | 5.055 | 0 | 0 | 1 | | | | | | | | |
| *NF-P15* | 2.492,0.802 | 4.730 | 0 | 0 | 0 | | | | | | | | |
| *SF30-P15* | 2.496,0.989 | 5.647 | 2 | 30 | 0 | | | | | | | | |
| *SF45-P15* | 2.505,0.994 | 5.758 | 2.5 | 45 | 0 | 13 | 274 | 0.15 | 233 | 41 | 40/60 | 844 | 1266 |
| *SF60-P15* | 2.499,0.999 | 5.734 | 3 | 60 | 0 | | | | | | | | |
| *PPF-P15* | 2.446,0.863 | 5.536 | 0 | 0 | 1 | | | | | | | | |
| *NF-P30* | 2.442,0.818 | 5.223 | 0 | 0 | 0 | | | | | | | | |
| *SF30-P30* | 2.360,0.969 | 5.773 | 2 | 30 | 0 | | | | | | | | |
| *SF45-P30* | 2.505,0.994 | 5.534 | 2.5 | 45 | 0 | | | 0.3 | 192 | 82 | | | |
| *SF60-P30* | 2.497,0.659 | 5.370 | 3 | 60 | 0 | | | | | | | | |
| *PPF-P30* | 2.433,0.992 | 5.322 | 0 | 0 | 1 | | | | | | | | |

## 4. Experimental specimens

### *4.1 Cubic specimens*

Cubic specimens were used for the measurement of compressive strength. In each set, concrete was made in 3 cubic 150 × 150 × 150 mm specimens, then cast and compacted in three layers each 50 mm thick. After 24 hours, specimens were demolded and cured in water.

### *4.2 Prismatic specimens*

The main purpose for making prismatic specimens was to investigate the effects of fibers on the compressive and flexural strengths of RCC pavements while undergoing flexural toughness tests. The specimens were made according to ASTMC1018 standard in 350 × 100 × 100 mm prisms by casting concrete in three layers each 50 mm thick using the Kango's vibrating hammer. They were tested at the age of 210 days and each test lasted for about 10-14 seconds.

## 5. Items of investigation

### *5.1 Compressive strength*

Specimens with the dimensions 150 × 150 × 150 mm underwent loading after 28 and 90 days. The loading direction was perpendicular to the concrete pouring surface, and the loading pace was

Table 6 Outcomes of compressive tests

| Mix design code | Maximum mean dry density ($kg/m^3$), standard deviation | Compressive strength ($N/mm^2$), standard deviation | |
|---|---|---|---|
| | | After 28 days | After 90 days |
| *NF-P0* | 2480, 5.715 | 33.93, 2.618 | 41.41, 4.872 |
| *NF-P15* | 2446, 5.715 | 33.71, 2.468 | 35.98, 4.760 |
| *NF-P30* | 2450, 18.991 | 29.82, 2.418 | 38.97, 5.743 |
| *SF30-P0* | 2477, 9.393 | 45.80, 1.336 | 50.67, 1.602 |
| *SF30-P15* | 2487, 32.221 | 42.16, 2.736 | 45.60, 1.720 |
| *SF30-P30* | 2462, 30.652 | 43.46, 3.649 | 49.36, 2.590 |
| *SF45-P0* | 2459, 41.492 | 40.95, 3.347 | 45.86, 2.408 |
| *SF45-P15* | 2499, 44.131 | 40.96, 1.377 | 52.42, 1.438 |
| *SF45-P30* | 2454, 33.993 | 37.63, 1.796 | 43.13, 7.062 |
| *SF60-P0* | 2480, 34.244 | 46.87, 2.493 | 55.97, 0.814 |
| *SF60-P15* | 2494, 6.481 | 43.33, 1.739 | 49.94, 2.910 |
| *SF60-P30* | 2474, 3.399 | 41.78, 3.478 | 50.45, 2.655 |
| *PPF-P0* | 2423, 22.171 | 40.86, 3.461 | 42.78, 4.209 |
| *PPF-P15* | 2439, 14.514 | 38.24, 2.926 | 45.27, 2.480 |
| *PPF-P30* | 2455, 12.754 | 37.85, 1.004 | 41.77, 3.425 |

around 5 mm/min. The apparatus had a loading capacity of 3000 kN and its measurement accuracy was 2.5 kN. The compressive test results for each mix design are reported in Table 6 as the mean value of three tests.

### *5.2 Flexural toughness*

This test was performed according to ASTMC1018 complied for the determination of flexural toughness of fiber-reinforced concrete beams. In fiberless concrete beams, however, the flexural strength is emphasized instead by modifying a modulus of rupture according to ASTMC78. As recommended by ASTMC78, the concrete beam undergoes a 4-point flexural test, as indicated in Fig. 6. In general, the rupture modulus is defined using the following formula

$$R = \frac{P\ell}{bd^2} \tag{1}$$

where $R$ is the rupture modulus, $P$ is the rupture load, $\ell$ is the specimen's length placed between the two supports, and $b$ and $d$ are the specimen's width and height, respectively. In this study, $b$ and $d$ have been taken to be 100 mm each equaling one third of the supported length, in order to conform to ASTMC78 and ASTM C1018-94b (2004). The apparatus had a 50 kN loading capacity and a 50 N measurement accuracy.

According to ASTMC1018, designed for the determination of fiber-reinforced beams, the specimen's behavior is recommended to be assessed even after initial rupture. The toughness is expressed as a function of the surface beneath the load vs. deflection diagram, as indicated in Fig. 7.

The specimen's behavior is studied using the following indices until a specified deflection is reached

$$I_5 = \frac{S(OACD)}{S(OAB)},\ I_{10} = \frac{S(OAEF)}{S(OAB)},\ I_{20} = \frac{S(OAGH)}{S(OAB)},\ R_{5,10} = 20(I_{10}-I_5),\ R_{10,20} = 20(I_{20}-I_{10}) \tag{2}$$

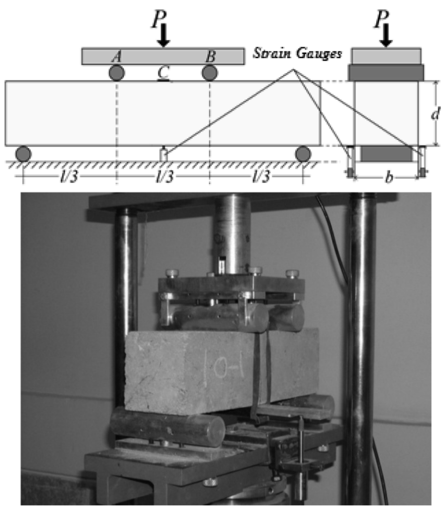


Fig. 6 Flexural toughness test according to ASTM C78

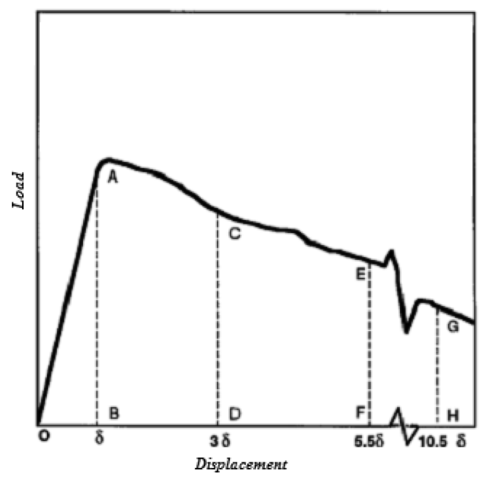


Fig. 7 Toughness Indices according to the load-displacement diagram

To properly measure deflection, two transducers were placed on the two sides of the specimen's cross section and the mean measurement was considered as the beam center deflection.

For our purposes, the triaxial testing apparatus, *Triset 50*, was used and a load of 50 kN was applied in each run. The loading speed was adjusted to 0.1 mm/min according to ASTMC1018, and its direction was set perpendicular to the concrete casting surface. Table 7 summarizes the results of flexural strength and Table 8 presents those of toughness indices and post-cracking load bearing in the mix designs containing steel fibers reported as the means of three tests.

Table 7 Flexural strength results

| Mix design | Mean rupture modulus - $N/mm^2$ (psi)), standard deviation |
|---|---|
| *NF-P0* | 6.70 (971.50), 1.2348 (179.046) |
| *NF-P15* | 6.05 (877.25), 0.6859 (99.455) |
| *NF-P30* | 3.78 (548.10), 0.4302 (62.379) |
| *SF30-P0* | 5.98 (867.10), 0.9316 (135.082) |
| *SF30-P15* | 5.71 (827.95), 0.3983 (57.753) |
| *SF30-P30* | 4.67 (677.15), 0.2994 (43.413) |
| *SF45-P0* | 5.86 (849.70), 0.3519 (51.025) |
| *SF45-P15* | 5.92 (858.40), 0.3982 (57.739) |
| *SF45-P30* | 4.91 (711.95), 0.5467 (79.271) |
| *SF60-P0* | 6.58 (954.10), 0.1134 (16.443) |
| *SF60-P13* | 6.15 (891.75), 0.6164 (89.378) |
| *SF60-P26* | 5.45 (790.25), 0.9693 (140.549) |
| *PPF-P0* | 5.23 (758.35), 0.3297 (47.806) |
| *PPF-P15* | 4.90 (710.50), 0.6404 (92.858) |
| *PPF-P30* | 4.26 (617.70), 0.2061 (29.884) |

Table 8 Toughness indices and the post-cracking load bearing capacities

| Mix design code | Toughness indices, standard deviation | | | Load bearing percentage after cracking, standard deviation | |
|---|---|---|---|---|---|
| | $I_5$ | $I_{10}$ | $I_{20}$ | $R_{5,10}$ | $R_{10,20}$ |
| *SF30-P0* | 4.48,0.033 | 6.83,0.446 | 9.98,1.635 | 47,8.524 | 32,13.021 |
| *SF30-P15* | 4.31,0.164 | 6.37,0.156 | 9.7,0.339 | 41,0.816 | 33,4.643 |
| *SF30-P30* | 4.27,0.506 | 7.34,0.513 | 12.39,0.203 | 61,2.494 | 50,4.497 |
| *SF45-P0* | 4.45,0.104 | 7.69,0.562 | 13.71,1.793 | 65,12.832 | 60,12.570 |
| *SF45-P15* | 4.27,0.170 | 7.39,0.850 | 13.17,2.646 | 62,15.434 | 58,18.055 |
| *SF45-P30* | 4.59,0.946 | 8.61,0.122 | 16.35,0.376 | 81,2.055 | 77,4.643 |
| *SF60-P0* | 4.41,0.156 | 7.72,0.894 | 14.07,2.410 | 66,15.063 | 63,15.456 |
| *SF60-P15* | 4.96,0.065 | 9.52,0.066 | 17.98,0.465 | 91,0.471 | 85,4.190 |
| *SF60-P30* | 4.63,0.198 | 8.63,0.484 | 15.8,0.817 | 80,5.715 | 72,4.497 |

## 6. Experimental results and discussion

### 6.1 Effect of pozzolans on compressive strength

The effect of pozzolans on compressive strength of specimens devoid of fibers is shown in Fig. 8.

1. When pozzolans were added, the 28-day compressive strength of specimens decreased in all designs devoid of fibers, i.e., by 0.64 and 12 percent (compared to the NF-P0 design) in the NF-P15 and NF-P30 designs, respectively. However, the influence of pozzolans on the compressive strength of designs with fibers is not adequately clear.
2. The 90-day compressive strengths of all specimens increased compared to their 28-day strengths. In the designs without pozzolans, it increased by 22, 11, 12, 19, and 5 percent in the NF, SF30, SF45, SF60, and PPF designs, respectively; in the designs containing 15% pozzolans, it increased by 7, 8, 28, 15, and 18 percent; and in the designs containing 30% pozzolans, it increased by 31, 14, 15, 21, and 10 percent. Thus, the only predictable effect caused by pozzolans on the long-term compressive strength is in the designs devoid of fibers, whereas no logical trend could be observed in the way pozzolans affected the long-term compressive strength in designs containing fibers. The only predictable influence in this case is that the maximum influence induced by pozzolans is detected in the 30-percent-pozzolan mix designs.

### 6.2 Effect of fibers on compressive strength

Depending on the amount of pozzolans added to each mix design, different effects were observed by fibers on compressive strength as shown in Figs. 9-14.

1. In the designs without pozzolans, compressive strength increased by 35, 21, and 28 percent in SF30, SF45, and SF60, respectively; in the designs containing 15% pozzolans, it increased by 25, 21, and 28 percent; and in the designs containing 30% pozzolans, it increased by 45, 26, and 40 percent. Thus, even though using steel fibers improves compressive strength, no logical order can be seen in the trend. Apropos of the 90-day compressive strength, the extent of influence is much like that of the 28-day compressive strength; i.e., the maximum effectiveness

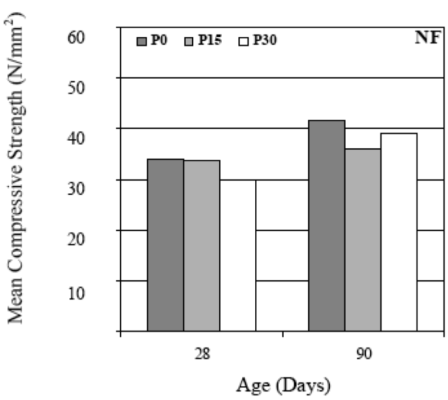


Fig. 8 Effect of pozzolans on the compressive strengths of mix designs without fibers

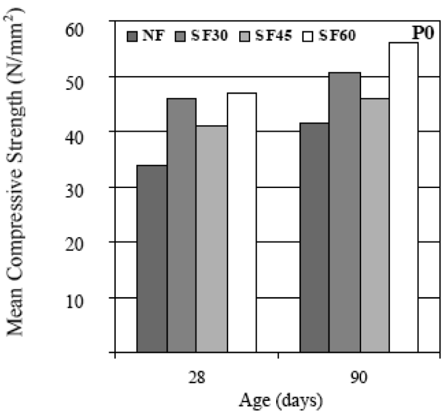


Fig. 9 Effect of steel fibers on the compressive strengths of mix designs without pozzolans

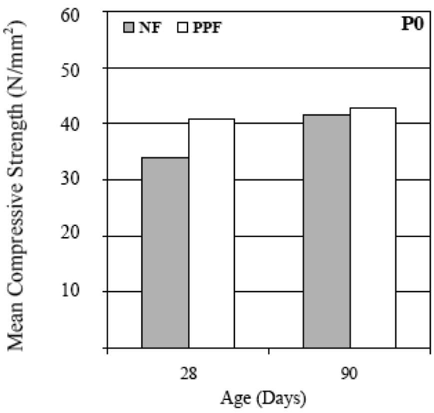


Fig. 10 Effect of PPF fibers on the compressive strengths of mix designs without pozzolans

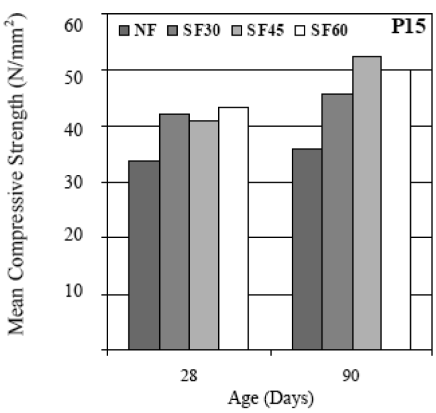


Fig. 11 Effect of steel fibers on the compressive strengths of mix designs with 15% pozzolans

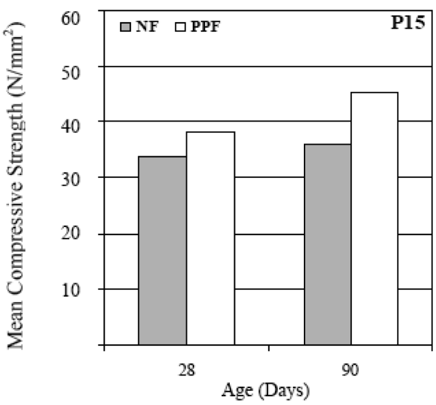


Fig. 12 Effect of PPF fibers on the compressive strengths of mix designs with 15% pozzolans

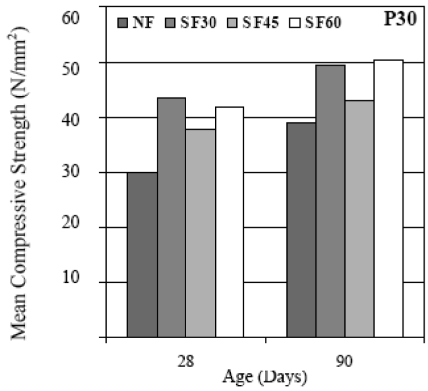


Fig. 13 Effect of steel fibers on the compressive strengths of mix designs with 30% pozzolans

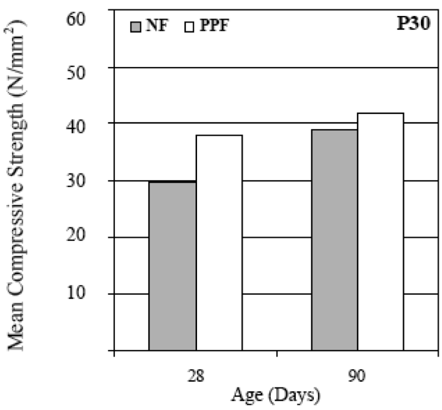


Fig. 14 Effect of PPF fibers on the compressive strengths of mix designs with 30% pozzolans

is observed with the 30 and 60 kg/m$^3$ steel-fiber-containing mix designs. This can be justified as follows: using fibers causes microcracks to overlap before extending to the whole concrete setting prior to rupture. Thus, the more fibers are used, the more overlapping occurs. Exceptionally, in the design containing 45 kg/m$^3$ for steel fibers, some other factors seem to be involved influencing compressive strength. These include unfavorable distribution of fibers and the mixing and compacting procedures. In other words, adding fibers will sometimes cause the inter-granular porosity to increase and, thereby, leads to reduced compressive strength.

2. Using poly-propylene fibers made an increasing trend in the compressive strength of all the specimens, for both 28 and 90-day periods. Compressive strength increased by 20, 13, and 27 percent in the designs containing 0%, 15%, and 30% pozzolan, respectively. This can also be justified by the overlapping role of poly-propylene fibers. Therefore, the effect of steel fibers is greater than that of poly-propylene fibers.

### *6.3 Effect of pozzolans on rupture modulus*

The results for the effect of pozzolans on rupture modulus are shown in Fig. 15.

As seen in the diagram, adding pozzolans decreased the rupture modulus. This is witnessed by the 10 and 44 percent decreases in NF-P15 and NF-P30 designs compared to the NF-P0 design; by 4.5 and 22 percent in the SF30-P15 and SF30-P30 designs compared to the SF30-P0 design; by 16 percent in the SF45-P30 design compared to the SF45-P0 design; by 6.5 and 17 percent in the SF60-P15 and SF60-P30 designs compared to the SF60-P0 design; and by 6.3 and 18.5 percent in the PPF-P15 and PPF-P30 designs compared to the PPF-P0 design. However, when steel fibers are used, the decreasing trend of the rupture modulus declines by using pozzolans. The reason lies in the role of fibers which increase the intergranular porosity in the concrete matrix. On the other hand, the volume of cementitious materials increases in the mix design when pozzolans are used as a cement replacement.

Moreover, a compound is produced under the effect of pozzolan-hydrated cement reaction, the solidity of which increases through time. The more cement exists in the mixture, the more pozzolans react with cement. This is the reason why the rupture modulus and strength of mix designs including 30% pozzolans are considerably lower than those with 15% pozzolans. These quantities reduced by 4 to 10 percent in the designs containing 15% pozzolans (compared to the

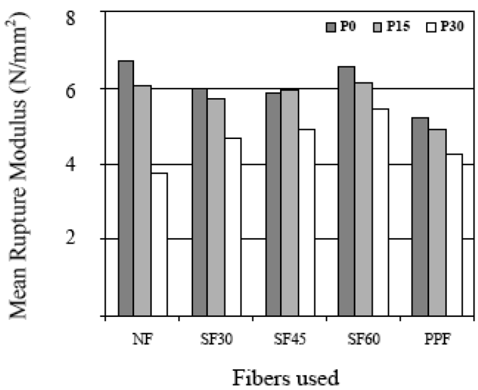


Fig. 15 Effect of pozzolans on the rupture modulus

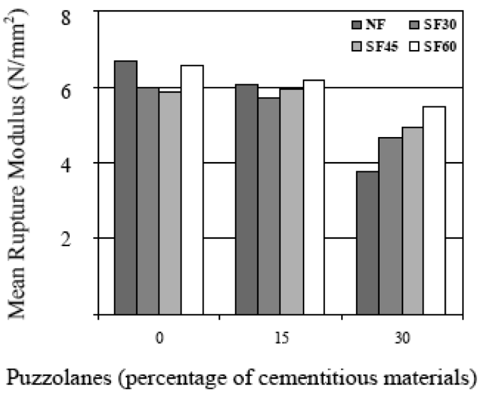


Fig. 16 Effect of steel fibers on the rupture modulus

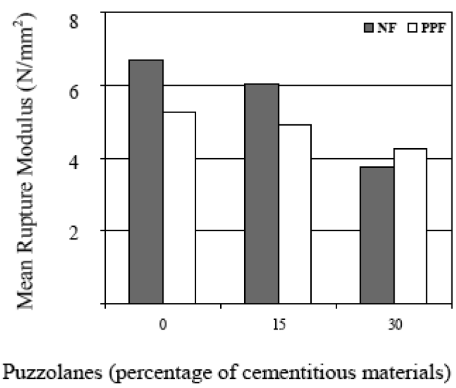


Fig. 17 Effect of PPF fibers on the rupture modulus

designs without pozzolans), and by 16 to 44 percent in those containing 15% pozzolans.

Similar to the case with steel fibers, when poly-propylene fibers are added, designs containing pozzolans adopt a lower rate of strength decline than that of fiberless designs.

### 6.4 Effect of fibers on rupture modulus

Figs. 16 and 17 illustrate the influence of fibers, their type and content, on the rupture modulus for steel and poly-propylene fibers, respectively, for different amounts of pozzolans used in each design. As seen in the Figures, in the design containing 0% or 15% pozzolans, steel and poly-propylene fibers not only lack any major effect on the rupture modulus of the fiberless designs, but also cause a decrease in the rupture moduli of some specimens, whereas in designs containing 30% pozzolan, the rupture modulus increases when steel fibers are added. When 30% pozzolans is used, rupture modulus increases by 8, 11, and 17 percent in the SF30, SF45, and SF60 designs (compared to the NF design), respectively.

### 6.5 Effect of pozzolans on toughness indices

As gathered from the experiments, no specific order can be observed in the way pozzolans affect the toughness indices. Examination of load-deflection curves in steel-fiber-reinforced designs reveals that the post-cracking behavior of the beams is mainly influenced by the fiber content in the design, and in this case pozzolans are almost inoperative.

### 6.6 Effects of steel fibers on toughness indices

The results for the effects of steel fibers on toughness indices are shown in Figs. 18-20 for different amounts of pozzolans. Clearly, toughness indices increase with increasing steel fiber content. The increase is mostly obvious for $I_{10}$ and $I_{20}$. $I_{10}$ increases by 7.5 percent in SF30-P30 compared to SF30-P0; by 12 percent in SF45-P30 compared to SF45-P0; and by 23 and 12 percent in SF60-P15 and SF60-P30 compared to SF60-P0, respectively. $I_{20}$ increases by 24 percent in SF30-P30 compared to SF30-P0; by 19 percent in SF45-P30 compared to SF45-P0; and by 28 and 12.3

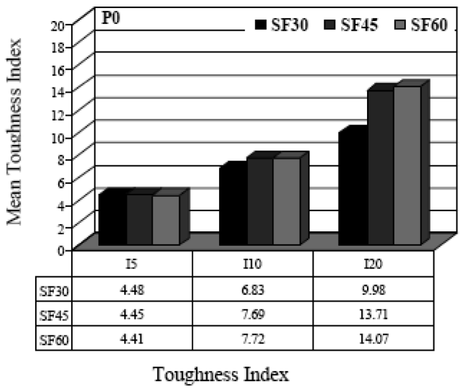


Fig. 18 Effect of steel fibers on the toughness indices of mix designs without pozzolans

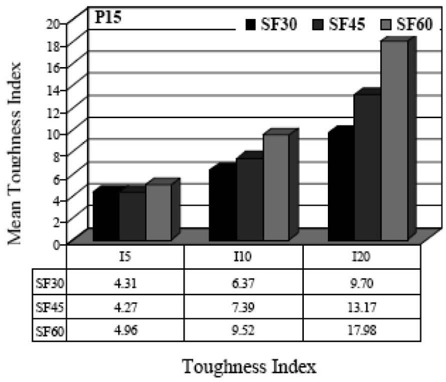


Fig. 19 Effect of steel fibers on the toughness indices of mix designs containing 15% pozzolans

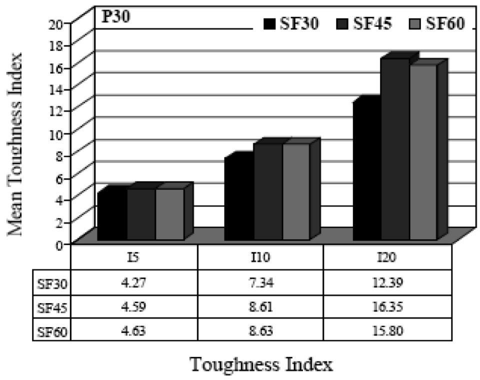


Fig. 20 Effect of steel fibers on the toughness indices of mix designs containing 30% pozzolans

percent in SF60-P15 and SF60-P30 compared to SF60-P0, respectively. However, a limited inconsistency can be seen in the results, which may be due to the distribution of fibers in the concrete matrix. In general, adding fibers not only increases the ductility, but also raises the energy absorption capacity of the specimens. That is the reason for the increased toughness indices of the fibers.

## 7. Conclusions

In this study, optimal mix proportions were first determined on a soil basis using optimum water content. In the second stage, various factors including the effects of pozzolans, steel and PPF fibers, and the simultaneous effects of fibers and pozzolans (in mixtures with optimum moisture content) on the mechanical properties of RCC were studied in detail. At a third stage, the effects of fibers on energy absorption and toughness indices were investigated in the light of the fact that RCC pavements are continually under dynamic, particularly impact, loads exerted by vehicles. The following summarize the findings of the present study:

- By adding pozzolans, the 28-day compressive strength decreased. Although the 90-day compressive strength increased in all the specimens, no distinguished trend could be observed regarding the effect of pozzolans on the 90-day compressive strength. The maximum increase in the compressive strengths occurred between 28 and 90 days.
- By using pozzolans, the rupture modulus decreased; however, adding fibers limited the intensity of this effect.
- The influence of pozzolans on the toughness indices was not considerable.
- Using steel fibers increased the compressive strength, the rate of which was found to be greater in the mix designs containing 30 and 60 kg/m$^3$ of fibers than in fiberless designs. Moreover, using PPF fibers had an increasing effect on the compressive strength, but its influence was found to be less than that of steel fibers.
- Utilization of steel fibers did not have any significant effect on the rupture modulus; in 30% pozzolan mix designs, however, the simultaneous effect of steel fibers on raising inter-granular porosity and that of pozzolans on increasing the volume of cementitious materials caused the rupture modulus to increase.
- By adding 1 kg/m$^3$ PPF fibers, no discernible influence was observed in the rupture modulus; however, it was found that rupture modulus was far less sensitive to fiber addition than to pozzolans.
- By using steel fibers, the toughness indices increased because of the increased energy absorption capacity of the concrete.
- In mix designs comprising 1 Kg/m$^3$ of PPF fibers, no remaining strength was measured right after rupture. Thus, more experiments are needed to obtain confident and decisive results on the effect of P.P.F fibers.
- The optimum design for the compressive strength was *NF-P30* for specimens without fibers, *SF60-P30* for those containing steel fibers, and *PPF-P30* for those with PP fibers. The maximum rupture modulus was obtained in *SF60-P30* for specimens containing steel fibers. Moreover, the mix designs *SF60-P15* and *SF60-P30* presented high values of the toughness indices. Overall, the mix design *SF60-P30* is recommended for obtaining the best results of mechanical properties of RCC pavements.

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