reported results in this paper, are based on the above size of specimen only.

Permeability

Specimens of size 90 mm diameter and 150 mm height were cast and tested after 28 days of normal curing. An experimental set up [Figure 2] was exclusively fabricated for determining the permeability of pervious concrete specimens, based on the falling head permeability method, proposed and reported by (Neithalath et al, 2006), as there is no equivalent standard prescribed in Indian codes. The above procedure has also been prescribed as the standard procedure in ACI 522R - 10.

Figure 2. Experimental setup of permeability testing

Total and Permeable voids

Specimens of size 90 mm diameter and 150 mm height were cast and tested after 28 days of normal curing, and the total voids were determined in accordance with ASTM C 1754/C 1754M - 12. Permeable voids ($\emptyset_{pv}$) were calculated using the procedure in the above code and using Equation (1).

$$\emptyset_{pv} = [1 - \frac{(w_2 - w_1)}{\rho v}] \text{ x } 100 \quad \text{-----} (1)$$

where w_1 is the specimen weight under water, w_2 is the weight of the specimen with the SSD condition, ρ is the density of water and v is the volume of the specimen (Seo, 2006).

RESULTS AND DISCUSSION

The compressive strength of pervious concretes for different binder contents (with 10% and 20% replacement of cement by fly ash) and percentage of fines are shown in Figure 3.

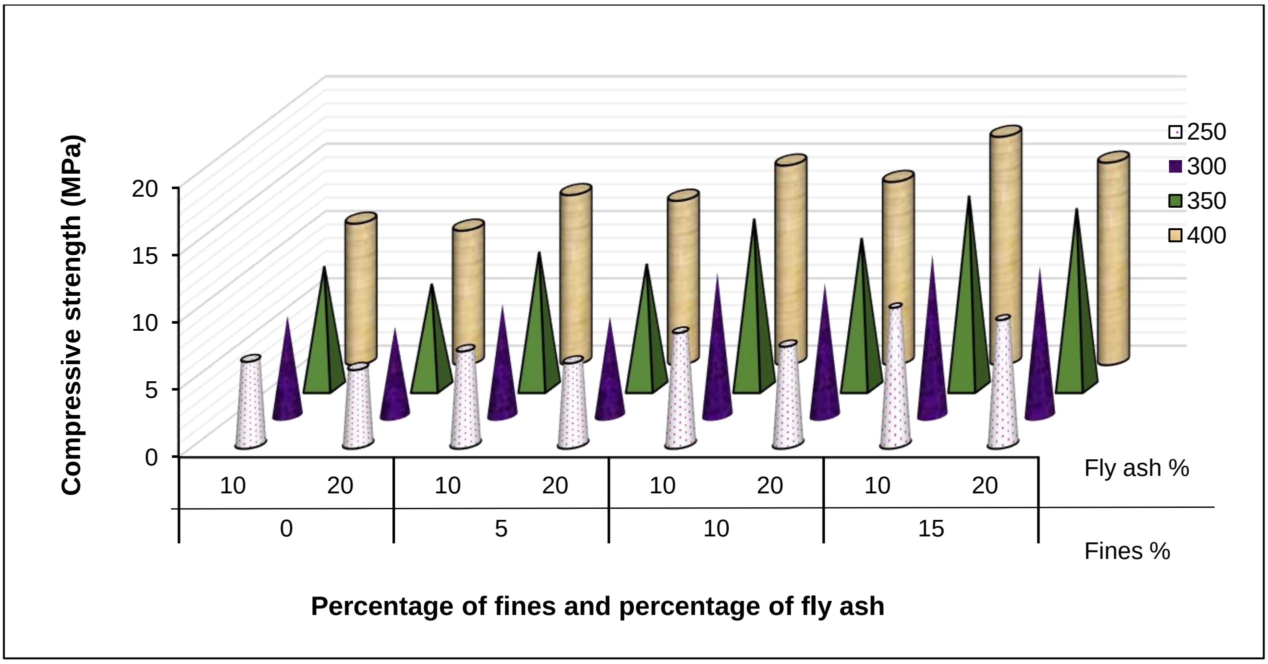

Figure 3. Compressive strength (28 days) of pervious fly ash- cement concrete for various binder contents (two levels of fly ash replacement) and percentage of fines

The actual compressive strength of pervious concretes in CF1 and CF2 - series (i.e. zero fines) increase with increase in binder content and the strength ranges from 5.70 to 8.83 MPa (at 28 days) for the range of binder contents considered. Incorporating the size effect, the estimated value of the above compressive strength ranges from 5.19 to 8.04 MPa (at 28 days) and the above strength range falls within the typical compressive strength reported (i.e. 2.8 to 20MPa) for pervious concretes in ACI522R - 10.

The above strength range also satisfies the typical strength range prescribed in the relevant Indian codes (Table 5) for use in lean cement concrete (LCC) as a base / sub - base layer of a flexible pavement. However, the strength range achieved even up to 20% replacement of cement by fly ash, (i.e. in CF1 and CF2 series of mixes) is less than the typical strength range prescribed for use in DLC in the relevant Indian codes. Thus, there is scope for improvement in the strength of pervious fly ash - cement concretes, for potential application / (s) as a sub – base / base material in pavements.

Table 5: Strength requirements for LCC and DLC as per Indian Standards

Sl. No	Purpose	Compressive strength (MPa)	Reference
1	Lean cement concrete (LCC) for base / sub base of flexible pavement.	3.7 - 7.2 (at 28 days)	IRC: 74 - 1979
2	Dry lean Concrete (DLC) for sub - base of rigid pavement.	7.0 (at 7 days) 10 (at 28 days)	IRC: SP: 49 -2014 IRC:58 - 2015

Addition of “fines” has increased the compressive strength of pervious fly ash - cement concretes, for all the range of fines-content considered. This is attributed to better packing of the matrix and improvement in interfacial bond, when compared to ‘no fines’ pervious concrete. Further, there is continuous improvement in the compressive strength due to the addition fines, ranging from marginal to high as the Binder content increases.

The strength behaviour of pervious fly ash - cement concrete, with and without fines, is similar, (Figure 4 and 5) for the range of binder contents considered, and is independent of fly ash replacement levels. As the minimum compressive strength of 10 MPa (at 28 days) is required for DLC to be used as a sub - base in a rigid pavement (Table 5), the strength range achieved pervious fly ash - cement concrete, excluding the binder content of 250 Kg/m^3 alone, fulfils the above requirement. Therefore, it can be stated safely that the minimum binder content for pervious fly ash - cement concretes, to be used in DLC in a rigid pavement with fines (10 and 15%) is 300 kg/m^3.

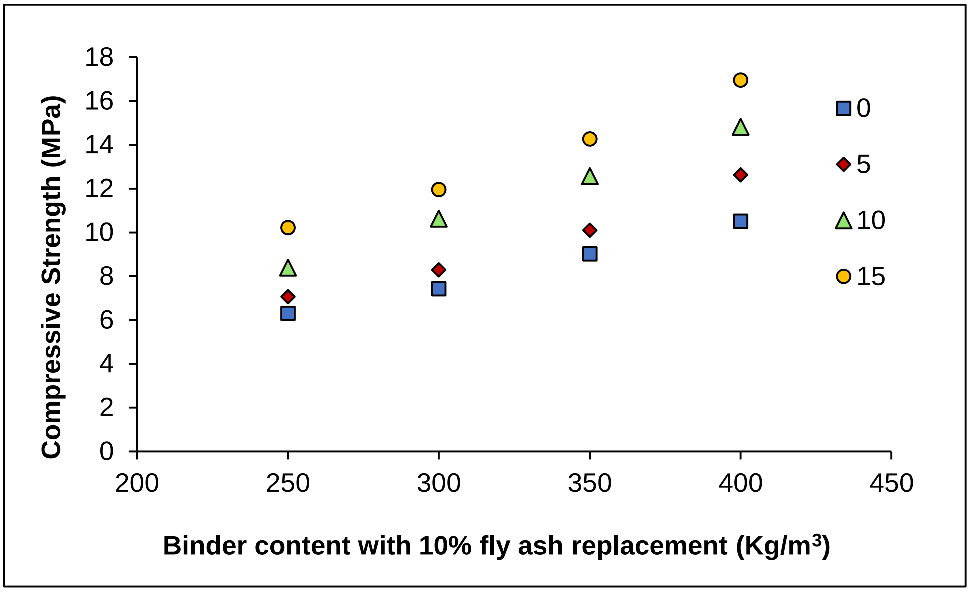

Figure 4. Compressive strength of pervious fly ash-cement for various binder contents and percentage of fines (10% fly ash replacement).

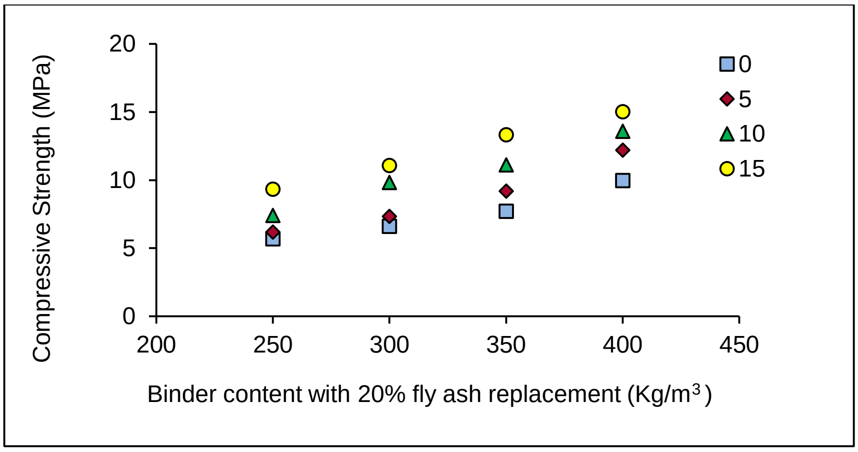

Figure 5. Compressive strength of pervious fly ash-cement for various binder contents and percentage of fines (20% fly ash replacement).

The variation of 7 - days compressive strength of pervious concretes is shown in Figure 6. It is observed that the average ratio of 7 to 28 - days compressive strength of pervious fly ash - cement concretes reported in this study, is 0.83 and 0.8, for with and without fines respectively, and for the range of parameters and binders considered. The above value is within the range (0.75 to 0.87), reported by several earlier investigators (Joshaghani et al, 2015; Aoki et al, 2012; Ravindrarajah et al, 2012 and Kevern et al, 2008) for pervious cement concrete. Further, the trend in the compressive strength at 7 - days and 28 - days are also similar. The above behaviour is in line with the reported behaviour of pervious cement concrete (Joshaghani et al, 2015; Aoki et al, 2012; Ravindrarajah et al, 2012 and Kevern et al, 2008).

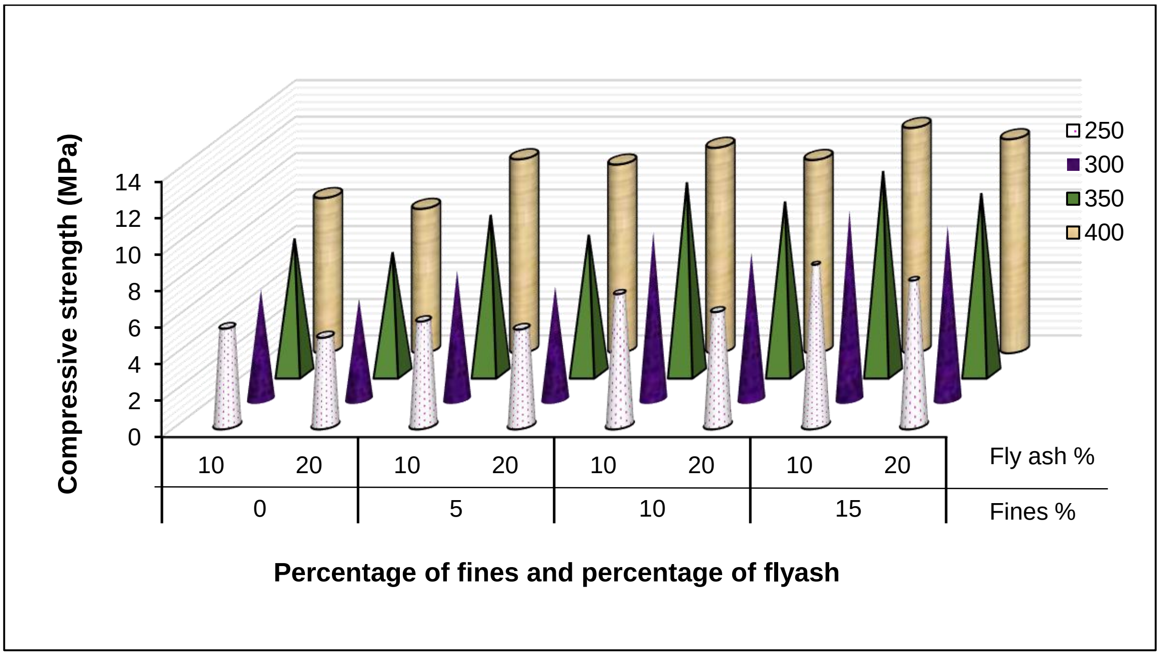

Figure 6. Compressive strength (7 days) of pervious fly ash - cement concrete for various binder contents (two levels of fly ash replacement) and percentage of fines.

Density with compressive strength

Density of pervious fly ash - cement concrete with and without fines ranges from 1849 to 2087 kg/m^3, for the two levels of fly ash replacement. The influence of fly ash content on the density of pervious concretes, is negligible. Considering the lowest value of density reported in this study for pervious fly ash - cement concrete, it is about 77% of the standard density of conventional concrete and comparable to the reported value of earlier investigators, for pervious concretes. The effect of density on the compressive strength of pervious concretes is shown in Figure 7. As the density of pervious fly ash - cement concrete increases, its compressive strength also increases.

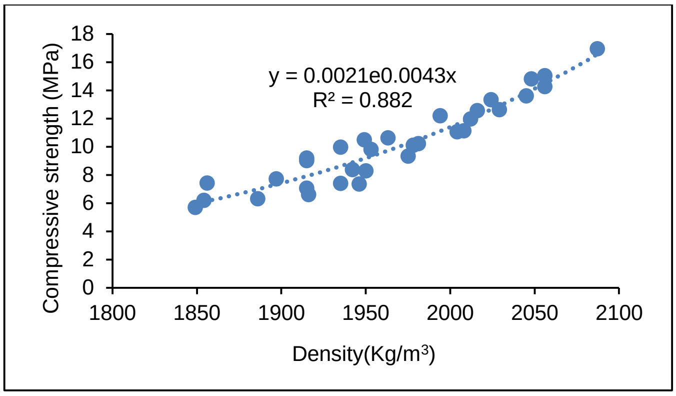

Figure 7. Effect of density on the compressive strength of pervious fly ash- cement concretes.

Flexural and split- tensile strength

Variation of flexural and split-tensile strengths of pervious fly ash - cement concrete for different binder contents with two levels of fly ash replacements and fines are shown in Figure 8 and 9, respectively. Both the above strength behaviour of pervious fly ash - cement concrete is similar to that of the corresponding compressive strength behaviour with respect to no fines and range of fines considered.

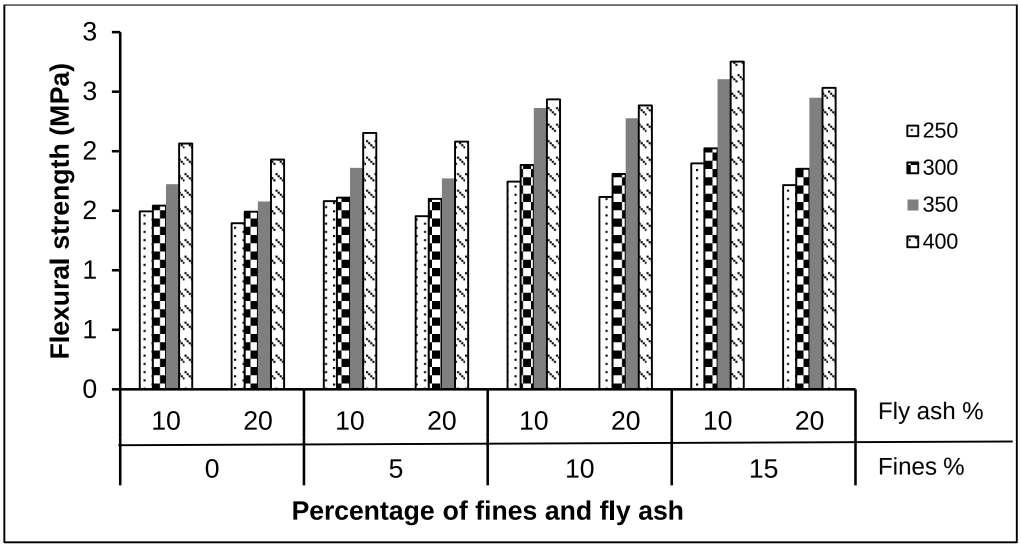

Figure 8. Flexural strength of pervious fly ash - cement concrete for various binder contents (two levels of fly ash replacement) and percentage of fines.

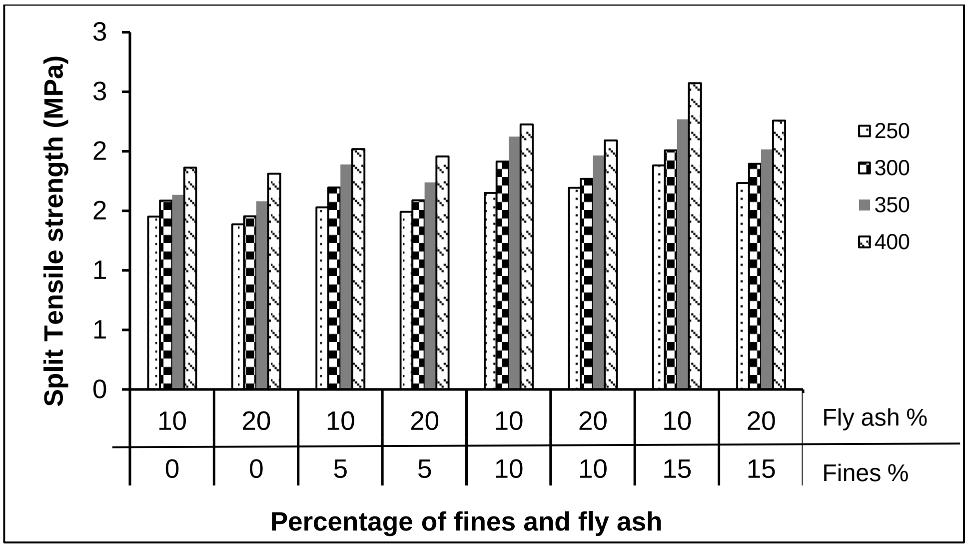

Figure 9. Split tensile strength of pervious fly ash - cement concrete for various binder contents (two levels of fly ash replacement) and percentage of fines.

The actual flexural strength attained is in the range of 1.40 to 2.06 MPa and 1.45 to 2.75 MPa for pervious fly ash - cement concretes with no fines and fines, respectively. Similarly, the split tensile strength attained is in the range of 1.45 to 1.86 MPa and 1.49 to 2.57 MPa for pervious fly ash-cement concretes with no fines and fines, respectively. It is observed that replacement of cement by fly ash, up to 20%, has only a marginal reduction in the flexural and split tensile strengths.

Influence of total voids on compressive strength characteristics

The total voids contents are in the range of 17.58 to 28.76% (for 10% fly ash content) and 13.55 to 24.76 % (for 20% fly ash content), and the corresponding compressive strength ranges from 6.30 - 16.95MPa (for 10% fly ash content) and 5.70-15.03MPa (for 20% fly ash content) respectively (Figure 10 and 11). The above total voids contents and the compressive strength of pervious fly ash - cement concrete (with 10% replacement of cement by fly ash) ranges are within the typical void content and strength ranges of pervious concrete reported in ACI 522 R - 10, whereas the total void content of pervious fly ash - cement concrete 20% replacement of cement by fly ash is slightly lesser.

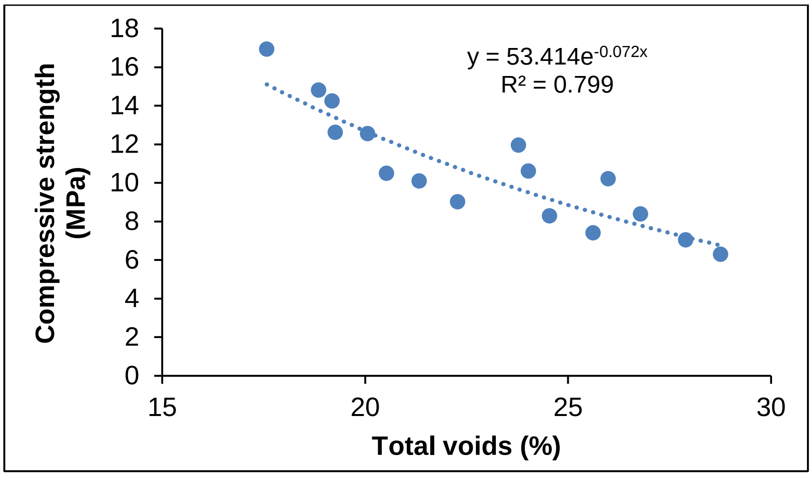

Figure 10. Effect of total void on the compressive strength of pervious fly ash - cement concretes (10% fly ash replacement).

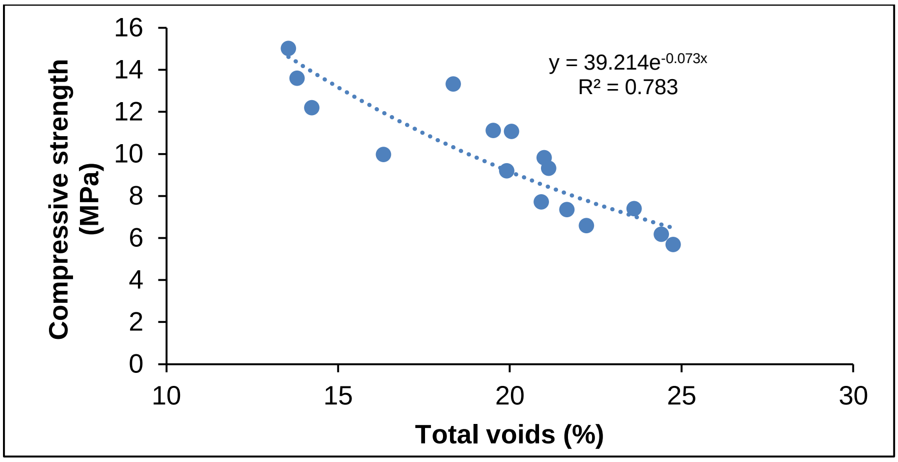

Figure 11. Effect of total void on the compressive strength of pervious fly ash - cement concretes (20% fly ash replacement).

In general, replacement of cement by fly ash has resulted in reduction in total voids content, and this is primarily attributed to the micro-filler effect of fly ash, thereby reducing the total voids in the pervious fly ash - cement concrete. In spite of the above effect, the resulting compressive strengths are within the typical range reported in ACI 522R - 10 for pervious concrete. Thus, addition of fly ash has resulted in beneficial effects from technical, economic and environmental considerations. The range of total voids of pervious concretes reported in this study, are within the range of void content reported (i.e. 14.95% to 40.14%) by several earlier investigators (Joshaghani et al, 2015; Bhutta et al, 2013; Hossain et al, 2012; Kuo et al, 2013; Ravindrarajah et al, 2012 and Kevern et al, 2008).

Permeability

The permeability of pervious concretes for different binder contents (with 10% and 20% replacement of cement by fly ash) and percentage of fines are shown in Figure 12. Permeability of pervious fly ash - cement concrete without fines, decreases with increase in binder content, and it ranges from 1.19 cm/s to 0.641 cm/s. Permeability of pervious fly ash - cement concrete with fines are in the range of 1.028 cm/s to 0.324 cm/s.

Addition of fines has decreased the permeability of pervious fly ash - cement concretes, for all ranges of fines considered and that the average reduction in permeability is 15.63%, for pervious fly ash - cement concrete. However, the overall reduction in permeability due to fines in pervious fly ash - cement concretes is even up to 60%. The above reduction in permeability is attributed to the combined effect of fines, and the type of binder (cement / fly ash) and binder content. The permeability of pervious concretes in this study is observed to be within the range (i.e. 0.1 to 2 cm/s) reported for pervious cement concrete, by various researchers (Kevern et al, 2008; Li et al, 2013; Martin et al, 2014; Qin et al, 2015; Haselbach et al, 2005 and Deo et al, 2011). It is to be noted that the higher value reported by a group of earlier researchers is for the case of using higher size coarse aggregates (i.e. 12.5 mm to 19 mm) (Joshaghani et al, 2016).

Influence of permeable voids on permeability characteristics

The trend in the compressive strength behaviour and permeability are inversely related, for all the range of binder contents (with 10% and 20% replacement of cement by fly ash) and percentage of fines considered, which is on expected lines (Figure 10,11 and Figure 13 and 14). Increase in permeable voids increases the permeability and it is independent of the binder content in pervious concretes (Figure 13 and 14). Permeable voids content range from 11.08 to 25.89%, considering all the range of parameters considered in this study. It is seen that the above range is 75% to 91% of the corresponding total voids, obtained in this study and the above fact can be considered as an advantage for various applications of pervious concrete.

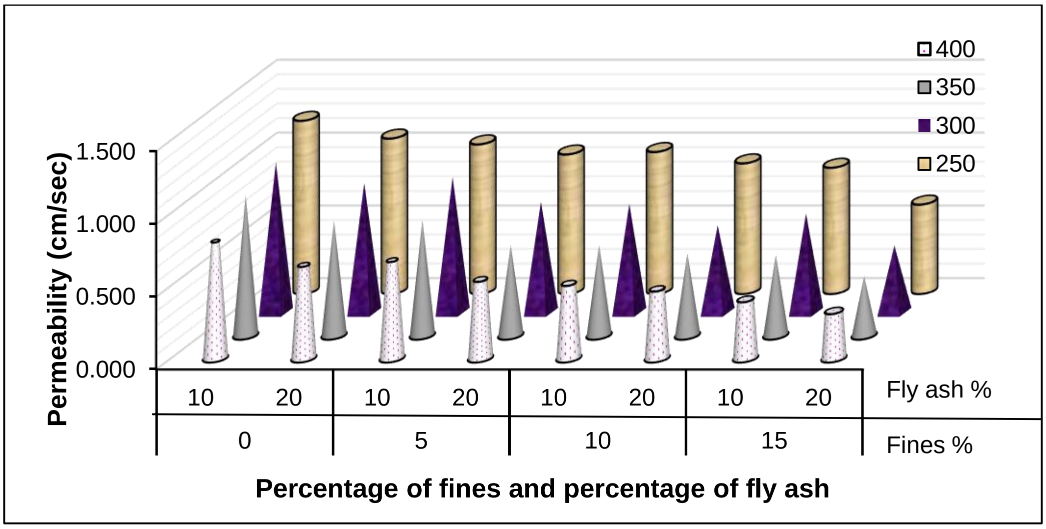

Figure 12. Permeability of pervious fly ash - cement concrete for various binder contents (two levels of fly ash replacement) and percentage of fines.

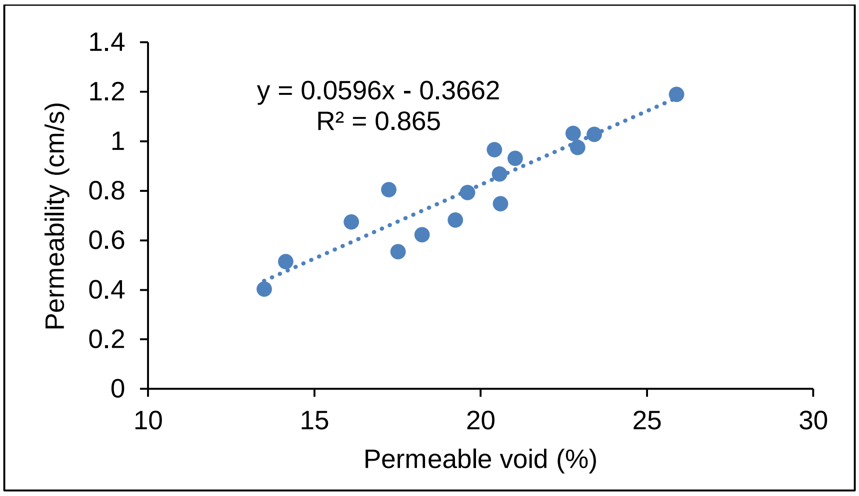

Figure 13. Effect of permeable voids on the permeability of pervious fly ash- cement concretes (with 10% replacement of fly ash).

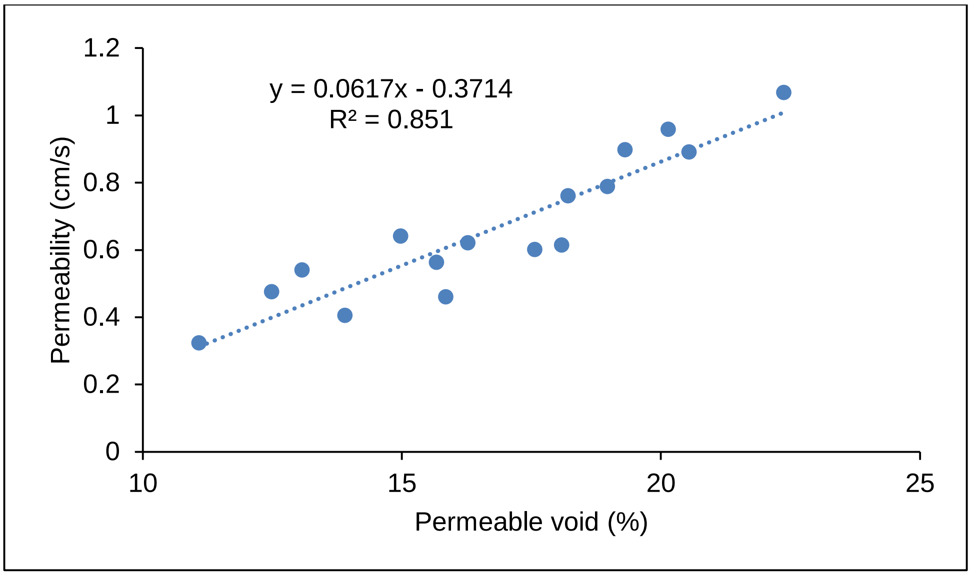

Figure 14. Effect of permeable voids on the permeability of pervious fly ash- cement concretes (with 20% replacement of fly ash).

CONCLUSIONS

The actual compressive strength of pervious fly ash - cement concrete with no fines, ranges from 5.70 to 8.83 MPa (at 28 days) for binder contents ranging from 250 to 400 kg/m^3 and the above strength range achieved has potential applications for use as a typical sub-base / base layer in flexible pavement, especially, in Indian conditions. Replacement of cement up to 20% by fly ash has reduced the above compressive strength range only marginally, and therefore it still has potential applications in flexible and rigid pavements, after improvement in the above strength by various established methods. However, if a minimum binder content of 300 kg/m^3 is used in pervious fly ash - cement concrete with 10% and 15% fines, then, it can be used for DLC as a sub - base in a rigid pavement, satisfying Indian standard code provisions. Addition of fine aggregates (ranging from 5 to 15%) has increased the compressive strength of pervious fly ash - cement concretes, ranging from ‘marginal’ to ‘high’. Strength behaviour of flexural and split- tensile strength is similar to that of the corresponding compressive strength behaviour of pervious fly ash - cement concrete, for all the parameters and their ranges considered in this study. Replacement of class C fly ash has resulted in reduction of total voids, which may be attributed primarily to the micro - filler effect of fly ash. There is a reduction of about 12 - 16% in the permeability of fly ash - cement pervious concretes, considering all the effect of no fines and fines in the above two systems.

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