Class C fly ash as a substitute for mineral fillers in asphalt mixtures

Sajjad Ali[1)] (ORCID ID: 0000-0003-0996-0457), **Muhammad Owais Raza Siddiqui**[2), 3), *)] (0000-0002-4687-2125), **Syed Muhammad Noman**[1)] (0000-0002-5236-4389), **Tahreem Beg**[2)] (0000-0002-7622-5105), **Danmei Sun**[3)] (0000-0003-3213-5615)

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Abstract: The influence of class C fly ash as a substitute for mineral aggregate on the stability and density of asphalt mixtures containing 3.5–6 wt% of bitumen was investigated. For the fly ash concentration (in relation to the replaced aggregate) 25, 50, 75 and 100 wt%, the optimal asphalt content (OAC) was determined, respectively, 5.75, 4.82, 4.42, 4.4 and 4 wt%. The stability increased with the increase in the content of fly ash. The results confirm the possibility of replacing mineral aggregates with fly ash.

Keywords: road construction, Marshall Mix method, asphalt, fly ash.

Popiół lotny klasy C jako zamiennik napełniaczy mineralnych w mieszankach asfaltowych

Streszczenie: Zbadano wpływ popiołu lotnego klasy C jako zamiennika kruszywa mineralnego na stabilność i gęstość nawierzchni asfaltowych zawierających 3,5–6% mas. bitumu. Dla stężenia popiołu lotnego (w stosunku do zastępowanego kruszywa) 25, 50, 75 i 100% mas. określono optymalną zawartość asfaltu (OAC) odpowiednio 5,75, 4,82, 4,42, 4,4 i 4% mas. Wraz ze wzrostem zawartości popiołu lotnego zwiększała się stabilność nawierzchni asfaltowych. Uzyskane wyniki potwierdzają możliwość zastąpienia kruszyw mineralnych popiołami lotnymi.

Słowa kluczowe: budownictwo drogowe, metoda Marshall Mix, asfalty, popiół lotny.

A well performing transport and communication structure is vital for country's development. Infrastructure investment directly affects country's economic growth as producers would find the best markets for their goods, reducing transportation time and cost, and generating employment opportunities [1]. Pakistan, being a developing country, has modes of transportation which include railways, roadways, and naval. With 161 million population, the country has reasonably developed transport infrastructure. It generates a total domestic transport load of around 239 billion passenger kilometers and 153 billion tons kilometers annually. The growth in demand for transportation services is considerably higher than the growth in GDP. Road transport is the backbone of Pakistan's transport system. Transport system is considered as one of the important sectors as it contributes to less than 10% of the GDP of Pakistan. Pakistan is contributing in making links between cities through motorways. These links play a major role in saving the transportation time for industries and agriculture goods. Quality Function Deployment is a method developed in Japan, starting in 1966 to help change the voice of the client into designer attributes for any product [2]. Quality Function Deployment can convert customer requirements into appropriate engineering characteristics in product design and development [3]. Through this method, time is reduced as well as customer requirements are fulfilled which overall reduces lifecycle cost and only important facts and figures are considered. Population explosion and rapid urbanization in Asian countries have brought complex mobility challenges for a vast majority of their people who also face issues of poverty, inequality, and limited access to basic services. Sustainable urban mobility paradigm has recently gained prominence in both developed and developing cities, yet the transition process raises important concerns and issues. Sociotechnical transition perspective provides a useful way to interpret the social and technical dynamics and complexities involved in sustainability transitions [4]. While the

1) Department of Civil Engineering, NED University of Engineering & Technology, University Road, 75270, Karachi, Pakistan.

2) Department of Textile Engineering, NED University of Engineering & Technology, University Road, 75270, Karachi, Pakistan.

3) School of Textiles & Design, Heriot-Watt University, TD1 3HF, Galashiels, UK.

*) Author for correspondence: orazas@neduet.edu.pk

average distances between activities are increasing with time, so are the issues of mobility and accessibility. Lack of access to public transport, poor quality of transportation infrastructure, rising levels of personal automobile ownership, and a persistent disregard of traffic regulations pose further issues to the already challenging mobility environment [5]. Growing industries of Pakistan are causing major increase in construction and maintenance of roadways [6]. This requires high amount of good quality material. The quality of the pavements can be increased by changing its mixture properties. There are many ways to change the properties of asphalt by using polymer, recycled aggregates, etc. Environmental pollution caused by waste products has become a serious worldwide issue and a challenge for sustainable development policy. Intensive exploitation of natural resources also results in irreversible changes in the natural environment, such as lowering groundwater level, vegetation degradation, and disturbances in the existing ecosystem. In modern industry, the elimination of wastes and protection of natural resources has become one of the major concerns nowadays. Pakistan being one of the urbanized countries produces high quantity of fly ash and residue of coal through its industries. Increase in the traffic demands a better quality of material that is being used in the pavement. For this purpose, utilizing fly ash in pavement can meet the requirements of increasing traffic load and improve the life of modified asphalt mixtures [7]. The construction and maintenance of roads require a large amount of high-quality materials. In order to preserve natural resources, a number of studies have been carried out to prove the usability of different waste and alternative materials, such as steel slag, waste rubber, waste polyethylene, recycled concrete, glass waste, paper industry effluent sludge, and asphalt aggregate, as well as construction and demolition waste [8–14], in concrete, mortars, and asphalt pavements.

The construction and maintenance of flexible pavement in Pakistan require a large quantity of good quality materials. On the other hand, increased rates of traffic growth and heavy axle load and conventional design methods cause different distress in flexible pavement. The development in the design and modification of asphalt mixtures is the daily need, which can not only make the pavement construction more economical but also perform better against different pavement distresses. Asphalt modification can be realized primarily through polymer modification; however, it is expensive due to the cost of raw polymer, requirements of skilled workers, and special equipment. Alternatively, asphalt mixture modification can be done by replacing common filler (*i.e.*, stone dust, lime, or cement), a fine material that mostly passes through 75 μ sieve (Ministry of Road Transport and Highways, 2013), or with other suitable materials, *i.e.*, shredded rubber, fly ash, marble powder, *etc*. Nowadays, due to the environmental and economic concerns researchers have extensively investigated the use of recycled waste material as additives in asphalt mixtures [15]. Fly ash is a waste material generated during the firing of wastes or ignition of materials to generate energy. Fly ash could be created during coal burning [16], municipal solid waste combustion, burning of rice husk [17, 18], and wheat straw ash [19], firing heavy and crude oil [20]. ASTM C618 [21] classified the fly ash in the following two categories:

1) class C fly ash,
2) class F fly ash.

The main difference between these two class ashes is on the basis of amount of silica, aluminum, calcium, and iron content present in the fly ash. Their chemical properties greatly depend upon the chemicals present in the fly ash.

Although fly ash has been used in concrete research for years, there is very limited application in asphalt pavement. This research was carried to examine the effect of fly ash on virgin 60/70 grade bitumen. The suitability of fly ash as a filler was assessed. Properties comparable to the control mixture were obtained. This study is based on the behavior of asphalt wearing coarse using class C fly ash (FA) as a replacement of mineral filler. For this purpose, various compacted and uncompressed specimens were prepared for the stability tests, flow and voids studies in mineral aggregates (VMA). Different bitumen content (from 3.5 wt% to 6.0 wt% at an increment of 0.5%) in controlled mixture as well as different percentage of fly ash (from 25 wt% to 100 wt% at an increment of 25 wt%) were used. The optimum asphalt content (OAC) was determined as 5.75 wt%, 4.82 wt%, 4.42 wt%, 4.40 wt%, and 4.0 wt% at 0 wt%, 25 wt %, 50 wt%, 75 wt%, and 100 wt% level of fly ash, respectively. For each OAC determined, two soaked and two unsoaked samples were prepared and tested, and a comparison was drawn between soaked and unsoaked values. The results were evaluated consequently.

EXPERIMENTAL PART

Materials

Bitumen, aggregates, and fly ash were used in experiments. The bituminous material was tested to investigate penetration grade (ASTM D586-19) [22], flash and fire point (ASTM D92-18) [23], softening point (ASTM D638) [24], float test (ASTM D139-95) [25], and ductility (ASTM D113-86) [26].

Natural aggregates were brought from a local area named Manghopir and fly ash was purchased from Matrixx Company, Pakistan. The tests performed on aggregates were: resistance to degradation of aggregates by abrasion and impact (ASTM C131-89) [27], specific gravity and absorption of coarse aggregates (ASTM C127-12) [28], impact value (ASTM C131) [29], and crushing value (BS 818-110) [30] by using the instruments of the Controls Sp. A. Company, Italy.

Fly ash was purchased from a local supplier. Physical and chemical properties of aggregates, asphalt, and fly ash are given in Tables 1, 2, and 3, respectively.

Table 1. Properties of aggregates

Property	Unit	Value
Bulk specific gravity (BSG) of compacted mixture	–	2.65
BSG of surface saturated dry condition	–	2.66
BSG of apparent condition	–	2.68
Absorption	%	0.48
LA abrasion	%	25.00
Impact value	%	14.67
Crushing value	%	19.00

Table 2. Properties of asphalt

Property	Unit	Value
Softening point	°C	43.8
Penetration grade	–	60–70
Flash/fire point	°C	130/270
Ductility	cm	110

Table 3. Properties of fly ash

Chemical composition, %	Class C fly ash	ASTM C 618 limits
Silicon oxide, SiO_2	32.9	–
Aluminum oxide, Al_2O_3	19.4	–
Iron oxide, Fe_2O_3	5.4	–
Total, $SiO_2+Al_2O_3+Fe_2O_3$	57.7	50 min
Sulfur trioxide, SO_3	3.8	5.0 max
Calcium oxide, CaO	28.9	–
Magnesium oxide, MgO	4.8	–
Potassium oxide, K_2O	0.3	–
Moisture content	0.8	3.0 max
Loss on ignition	0.6	6.0 max
Physical properties		
Fineness, % retained on #325 sieve	15.9	34 max
Pozzolanic activity index, %	79	75 min
Water requirement, %	89	105 max
Soundness, autoclave expansion, %	0.11	0.8 max
Specific gravity	2.58	–

Table 4. Gradation of compacted mixture

Sieve designation (passing)		Sieve designation (retained)		wt%
mm	Inch	mm	inch	
25	1	19	¾	5.0
19	¾	9.5	⅜	32.0
9.5	⅜	4.75	4	20.5
4.75	4	3.38	8	13.5
3.38	8	1.18	16	20.5
1.18	16	0.075	200	3.5
0.075	200	Pan	Pan	5.0

Methods

Stability and flow were tested with a Marshall Stability apparatus. Washed, dried and sieved aggregates were used for the tests. The gradation condition is given in Table 4. For every level of asphalt percentage and every level of FA replacement, three samples were produced for compacted specimens. Therefore, a total number of 90 samples was produced for compacted samples. For uncompacted samples, two samples were prepared at each level of FA and percentage of asphalt, a total was 60 samples produced for uncompacted specimens. Samples of dry mixtures were prepared by weighing and mixing the exact proportion of sieved aggregates and fly ash before keeping them in an oven at 150°C to ensure that the samples were uniformly heated with the mixing spoon, moulds and asphalt separately in order to complete the whole experiment within the temperature limits. Then the aggregates were mixed with asphalt's specific percentage on a hot plate ensuring that the aggregates were thoroughly mixed with asphalt. After that the asphalt mixtures were again kept in the oven at 150°C in order to maintain the temperature required to perform the experiment. Different bitumen content (from 3.5 wt% to 6.0 wt% at an increment of 0.5 wt%) in controlled mixture as well as different percentage of fly ash (from 25 wt% to 100 wt% at an increment of 25 wt%) were used.

RESULTS AND DISCUSSION

Air voids

The air voids (%) are used to determine the physical characteristics of the aggregates and asphalt mixtures. The percentage of voids in mineral aggregates was calculated using Equation 1.

$$\mathrm{VMA} = \left[1 - G_{mb} \cdot \frac{1 - P_b}{G_{sb}}\right] \cdot 100 \tag{1}$$

where:
VMA – voids in mineral aggregates
G_{mb} – specific gravity of compacted mixture (bulk)
P_b – asphalt content by weight of mixture (%)
G_{sb} – specific gravity of aggregates (bulk).

The VMA results of various samples are shown in Fig. 1. It could be noticed, that the curves initially decreased with the increase of asphalt content (AC) and after reaching the minimum value, the curves increased with the increase of AC until reaching maximum V_a (air voids content). The minimum value was achieved at 50 wt% FA and the maximum value was achieved at 0 wt% FA. The percentage of air voids was found using Equation 2.

$$V_a = \left[1 - \frac{G_{mb}}{G_{mm}}\right] \cdot 100 \tag{2}$$

where:
V_a – air voids ratio

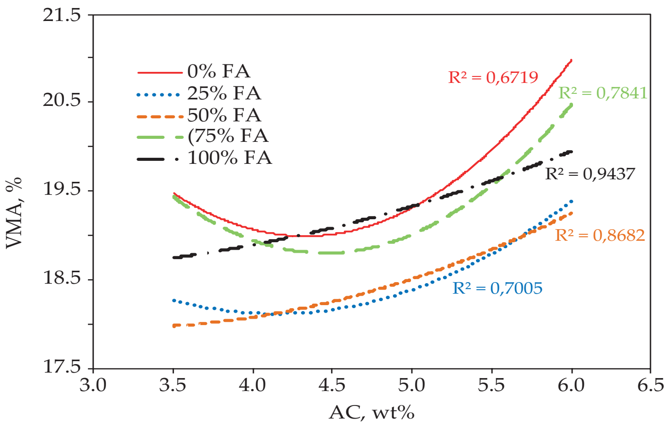

Fig. 1. VMA for different fly ash levels

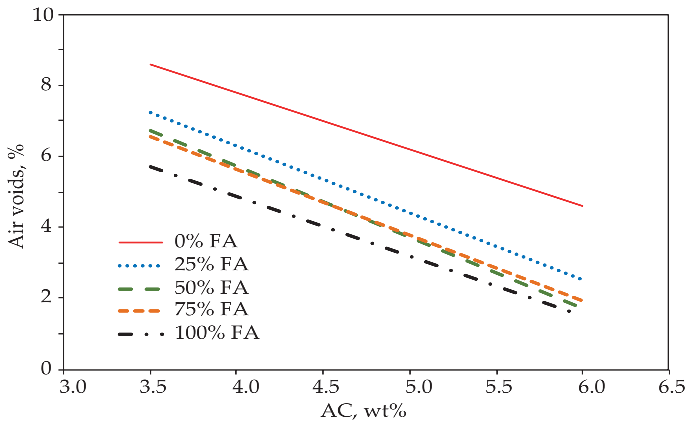

Fig. 2. Percentage of air voids for different fly ash levels

G_{mb} – bulk specific gravity of compacted mixture
G_{mm} – maximum theoretical specific gravity.

It can be seen in Fig. 2 that the air voids amount was reduced with the increase in the AC at all levels of FA replacement, because of asphalt filling the air voids and therefore reducing their volume.

Specific gravity

The maximum theoretical specific gravity was found by using Equation 3.

$$G_{mm} = \left[\frac{A}{A+B-C}\right] \tag{3}$$

where:
A – dry mass of sample
B – mass of cap and bowl with water at 25°C
C – mass of cap, bowl, sample, and water at 25°C.

Fig. 3 shows density variation of the mixture with the increase in asphalt content at all levels of FA. Density initially increased with the increase of AC. The decrease started because of the lighter weight of material. The maximum density was achieved at 25 wt% FA replacement with mineral filler.

Stability and float tests

The Marshall stability is described as the strength of the designed mixture whereas the flow indicates the vertical distortion of the specimen. The stabilities of different tested samples are shown in Fig. 4. The curves initially increased with the increase of AC, caused by higher asphalt content providing greater stability, then decreased after attaining the maximum value. The maximum stability was achieved at 100 wt% FA.

Flow describes the change in dimension after the application of load. The flow increased with the increase of the AC due to the reduction of friction between the aggregates. The maximum flow was achieved at 50 wt% FA replacement (Fig. 5).

The values of stability/flow ratio are plotted in Fig. 6. The curves show the direct relationship between AC and stability/flow ratio at all levels of FA replacement. The stability/flow ratio decreased with the increment of the asphalt content at all levels of FA.

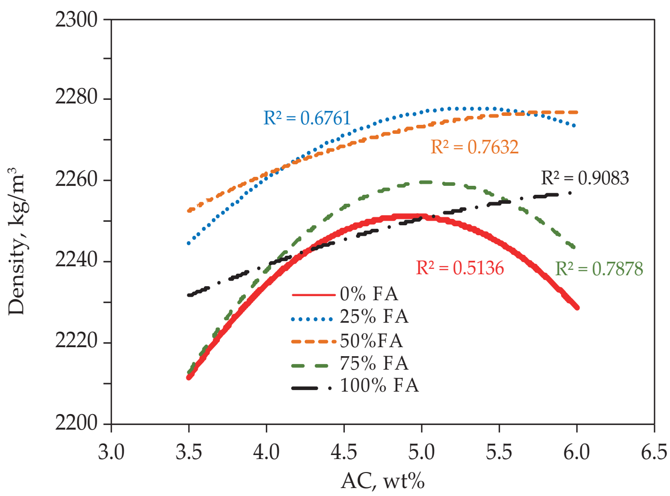

Fig. 3. Density for different fly ash levels

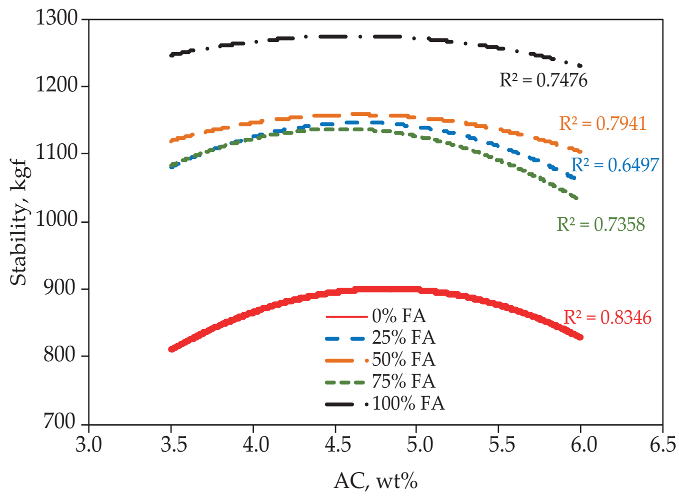

Fig. 4. Stability for different fly ash levels

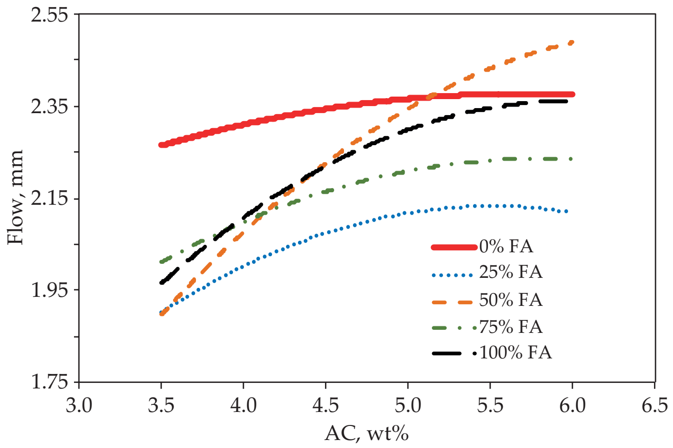

Fig. 5. Flow for different fly ash levels

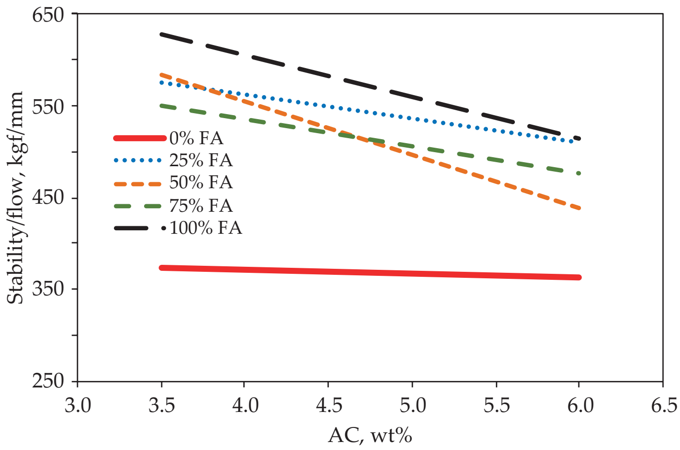

Fig. 6. Stability/flow ratio for different fly ash levels

Optimum asphalt content

Optimum asphalt content (OAC) at each level of FA was obtained by averaging the Asphalt Institute manual (AIM) and National Highway Authority (NHA) specifications [31], emerging to be 5 wt% of air voids. Fig. 7 shows the relationship between OAC and the level of FA replacement. OAC decreased with the increase in the level of FA. The reason was the fly ash hydrophobicity (non-water settability) in nature that would result in the decrease in AC.

The stability, density, VMA, and flow at each FA level for soaked and unsoaked samples are shown in Figs. 8–11. The stability for soaked samples was found to be lesser as compared to unsoaked ones. The major reason of this occurrence was the increased amount of water weakening the bonds between aggregates. The density for the soaked samples was higher than for the unsoaked ones because of the absorbance of water in voids. The value of VMA for the unsoaked samples was higher as compared to the soaked samples except for 75 wt% FA replacement. The value of flow for unsoaked samples was lesser as

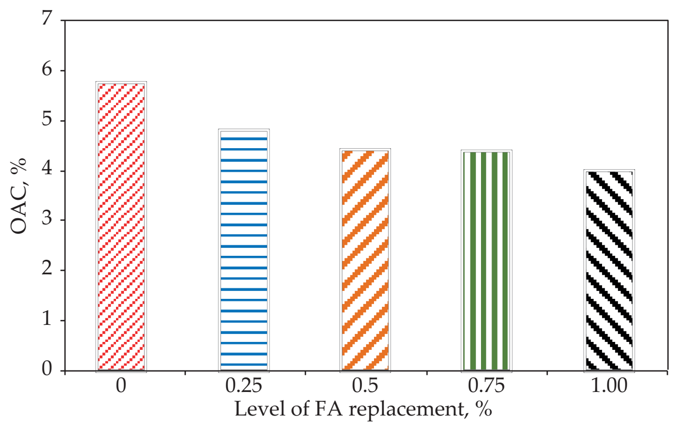

Fig. 7. OAC for different fly ash levels

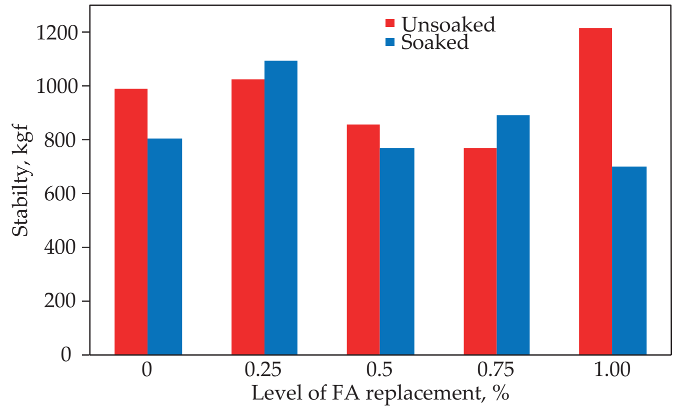

Fig. 8. Unsoaked and soaked samples' stability data at OAC

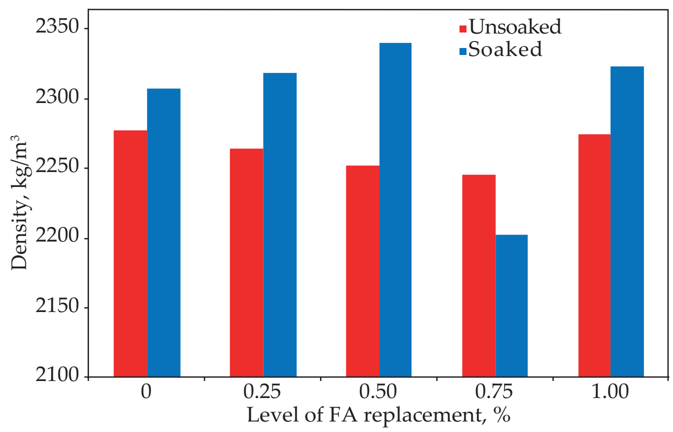

Fig. 9. Unsoaked and soaked samples' density data at OAC

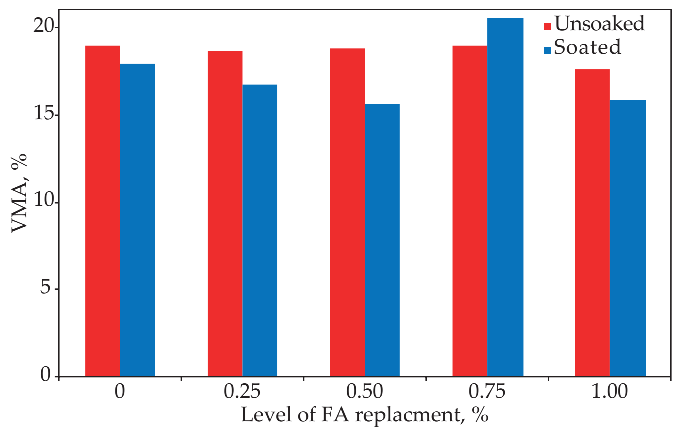

Fig. 10. Unsoaked and soaked samples' VMA data at OAC

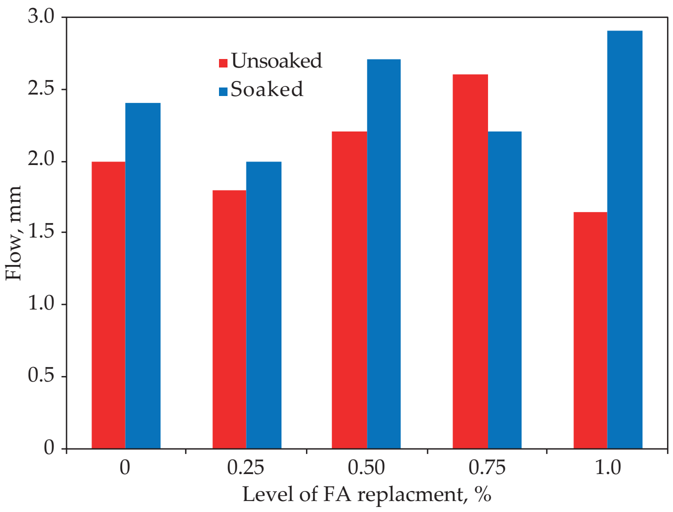

Fig. 11. Unsoaked and soaked samples' flow data at OAC

compared to the soaked samples as a consequence of the absorbance of water.

CONCLUSIONS

The effects of class C fly ash as an additive replacing mineral filler on the stability, air voids, and density of asphalt mixtures were investigated. Optimum asphalt content was determined. The fly ash requires lesser asphalt as compared to natural aggregates for absorption and binding. Optimum stability of unsoaked sample was achieved at 100% replacement of mineral filler with fly ash at 4 wt% OAC. Optimum stability of soaked sample was achieved at 25 wt% replacement of mineral filler with fly ash at 4 wt% OAC. Reduction in OAC with increasing FA level and increasing stability was achieved at all FA levels. The stiffness of asphalt-aggregate mixtures is of paramount importance in determining the quality of the pavement performance and is fundamental to the analysis of pavement response to traffic loading. Maximum stiffness of asphalt was observed at 100 wt% replacement in unsoaked samples and 25 wt% replacement in soaked ones. Lower VMA value means that the intergranular space available for asphalt binder is reduced. This reduces the amount of effective asphalt binder that can be used in the mixture, which in turns, leads to a lower binder film thickness around the aggregate particles. It is believed that a minimum VMA requirement is necessary to ensure adequate binder content and durability of the designed mixture [32]. This was witnessed at 50 wt% replacement (soaked sample) and 25 wt% replacement (unsoaked sample). The obtained results indicate that the stability, VMA and stiffness of the asphalt mixture increase with the increase in the fly ash content.

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