Effects of Binary and Ternary Cementitious Blends on the Mechanical Properties of Self Compacting Concrete

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ABSTRACT

Background: The main advantage of using ternary blended concrete is to eliminate the drawbacks of the particular supplementary cementitious materials through combining with other superior quality material and reduce the overall cost of the concrete production. It is also useful to enhance the structural properties of concrete. Objective: In this paper, fresh state and mechanical properties of self compacting concrete (SCC) with binary and ternary cementitious blends of metakaolin (MK) and Fly ash (FA) were evaluated and their inter-relationships discussed. For this purpose, different mixtures were prepared with different amounts of MK and FA and ordinary Portland cement (OPC) was replaced by 5% to 40% of MK and FA. Results: As a result, of increasing the percentage of MK, FA and MK+FA, the mechanical properties of SCC considerably improved. One interesting point is observed that the sample incorporating the ternary blend of cement with 15% MK and 15% FA showed better workability and mechanical properties than that of the normal SCC sample without MK or FA. Conclusion: From the results, it can be concluded that this blends was proved to be the optimum combination (15%MK+15%FA) for achieving maximum synergic effect in fresh, strength properties of SCC. It can be also concluded that a strong interrelationships between UPV and mechanical properties of MK+FA blended SCC mixes was observed for compressive strength, splitting tensile strength and DME (R²=99.9%).

INTRODUCTION

Self compacting concrete (SCC) was first developed in 1988 in the Japan due to gradual reduction of skilled labour in the construction industry. Hajime et al. (2003) indicated that SCC can be achieved without segregation and high deformability in the following three ways: limiting aggregate content; low water powder ratio and the use of superplasticizer. Nowadays SCC gains much popularity throughout the world because of its interesting structural properties. Hemant Sood et al. (2009) indicated that SCC is not completely accepted due to higher cost, the lack of standard specifications and testing procedures and the SCC is only treated as special concrete. Recent results (Nor Atan and Hanizam Awang, 2011) denoted that the reason for the increased cost of SCC production is the use of higher powder (cement) content which can be reduced by using various mineral admixtures such as rice husk ash, fly ash, metakaolin etc. as partial replacement of cement. Mineral admixtures can also improve the structural properties of the SCC.

Metakaolin (MK) is an amorphous material obtained by dehydrating kaolin at a temperature of approximately 800° C. Khatib and Wild (1996) concluded that the high reactivity of MK with cement and its ability to accelerate cement hydration makes it different from other pozzolanic materials. Shekarchi et al. (2010), Ambroise (1994) found that MK accelerates the initial setting time and improves the mechanical and transport properties, especially attaining high compressive strength at early age.

Fly ash (FA) is a by-product of coal-fired electric power plants which is commonly used as pozzolanic material in blended cement (Chindaprasirt and Rukzon, 2012). Yahia et al. (1999) denoted that the use of fly ash in SCC, enhance the transport properties as well as later-age strength and reduce the micro cracks in SCC. Research results (Khurana and Saccone, 2001) indicated that the replacement of cement by 30% of fly ash can significantly improve fresh state properties. The use of fly ash reduces the demand for cement, fine fillers and sand, which are required in high quantities in SCC. Moreover, the incorporation of fly ash also reduces the need for viscosity enhancing chemical admixtures.

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In this study, the effect of MK in combination with and without FA on fresh state and mechanical properties such as slump flow test, V-Funnel test, L-box test, compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV) and dynamic modulus of elasticity were experimentally determined. Interrelationships of various measured mechanical properties are discussed in this paper.

**MATERIALS AND METHODS**

### 2.1 Materials:

Ordinary Portland cement (OPC) conforming to Indian standard code IS 8112-1995 was used. The sieve analysis of fine aggregate (F.A) and coarse aggregate (C.A) was carried out in accordance with IS 383:1970 code provision. The results of sieve analysis as well as physical properties of F.A and C.A are presented in Table 1. Commercially available MK was used for this study and FA was obtained from the Tuticorin thermal power station, Tamilnadu state, India (conforming to IS 3812-1981).

<table>
<thead>
<tr>
<th>Mix designation</th>
<th>W/B</th>
<th>Quantities (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC(100% OPC)</td>
<td>0.55</td>
<td>Water 220, OPC 400, MK 0, FA 0, SP 8, F.A 880, C.A 800</td>
</tr>
<tr>
<td>SCC-MK05</td>
<td>0.55</td>
<td>220 380 20 8 880 800</td>
</tr>
<tr>
<td>SCC-MK10</td>
<td>0.55</td>
<td>220 360 40 8 880 800</td>
</tr>
<tr>
<td>SCC-MK15</td>
<td>0.55</td>
<td>220 340 60 8 880 800</td>
</tr>
<tr>
<td>SCC-MK20</td>
<td>0.55</td>
<td>220 320 80 8 880 800</td>
</tr>
<tr>
<td>SCC-MK25</td>
<td>0.55</td>
<td>220 300 100 8 880 800</td>
</tr>
<tr>
<td>SCC-MK30</td>
<td>0.55</td>
<td>220 280 120 8 880 800</td>
</tr>
<tr>
<td>SCC-FA05</td>
<td>0.55</td>
<td>220 380 20 8 880 800</td>
</tr>
<tr>
<td>SCC-FA10</td>
<td>0.55</td>
<td>220 360 40 8 880 800</td>
</tr>
<tr>
<td>SCC-FA15</td>
<td>0.55</td>
<td>220 340 60 8 880 800</td>
</tr>
<tr>
<td>SCC-FA20</td>
<td>0.55</td>
<td>220 320 80 8 880 800</td>
</tr>
<tr>
<td>SCC-FA25</td>
<td>0.55</td>
<td>220 300 100 8 880 800</td>
</tr>
<tr>
<td>SCC-MK05+FA05</td>
<td>0.55</td>
<td>220 360 20 8 880 800</td>
</tr>
<tr>
<td>SCC-MK10+FA10</td>
<td>0.55</td>
<td>220 320 40 8 880 800</td>
</tr>
<tr>
<td>SCC-MK15+FA15</td>
<td>0.55</td>
<td>220 280 60 8 880 800</td>
</tr>
<tr>
<td>SCC-MK20+FA20</td>
<td>0.55</td>
<td>220 240 80 8 880 800</td>
</tr>
</tbody>
</table>

The physical and chemical analysis of OPC, MK and FA was carried out according to relevant Indian standard (IS) code provisions. Superplasticizers (SP) were used to increase the workability of SCC. For this work, Sulphonated Naphthalene Polymers based SP with the specific gravity of 1.220 was used as a high range water reducer (conforming to IS: 9103:1999 and ASTM-C-494 Type 'F' depending on the dosages used) to improve the performance of SCC.

### 2.2 Mix proportion and preparation of the specimen:

The mix was proportioned according to the previous study as well as EFNARC guidelines to produce M30 grade SCC without segregation and bleeding. For this study totally seventeen SCC mixes (MK and FA ranging from 0%, 5%, 10%, 20%, 30% and combination of MK and FA ranging from 10%, 20%, 30% and 40% with one normal SCC) were prepared with a water to binder (W/(C+MK or FA or MK+FA) ratio of 0.55 and 2% of superplasticiser. These mixes were designated as SCC (100% OPC) and SCC-MK05/FA05/MK05+FA05…….SCC

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**Table 1:** Sieve analysis and physical properties of Fine and Coarse aggregates.

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Fine aggregate (% of passing)</th>
<th>Coarse aggregate (% of passing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>12.5</td>
<td>100</td>
<td>90.1</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>10.4</td>
</tr>
<tr>
<td>4.75</td>
<td>99.9</td>
<td>0.00</td>
</tr>
<tr>
<td>2.36</td>
<td>99.1</td>
<td>0.00</td>
</tr>
<tr>
<td>1.18</td>
<td>83.1</td>
<td>0.00</td>
</tr>
<tr>
<td>0.60</td>
<td>58.3</td>
<td>0.00</td>
</tr>
<tr>
<td>0.30</td>
<td>10.0</td>
<td>0.00</td>
</tr>
<tr>
<td>0.15</td>
<td>0.70</td>
<td>0.00</td>
</tr>
<tr>
<td>Pan</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Bulk density(kg/m³)</td>
<td>1752</td>
<td>1640</td>
</tr>
<tr>
<td>Specific Gravity (g/cm³)</td>
<td>2.53</td>
<td>2.78</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>2.01</td>
<td>0.36</td>
</tr>
</tbody>
</table>
The SCC was mixed for 5 minutes in a laboratory. For all mixes, three cube specimens of 100mm size were cast for compressive strength testing, and before compressive strength testing all cube specimens were used for ultrasonic pulse velocity testing. Three cylindrical specimens of 150 mm diameter and 300 mm height were also cast for determining the splitting tensile strength. After casting, all the specimens were left in the casting room for 24 hours. After 24 hours, the specimens were demoulded and immersed in water curing tank up to the time of testing.

2.3 Testing of Methods:
To check the fresh state properties of SCC, Slump flow test, V-funnel test and L-box tests were performed in the laboratory according to EFNARC specifications. Mineralogical and particle size analysis of MK and FA were carried out by X-ray diffraction analysis and particle distribution curve respectively. All the mechanical property tests were performed after 28 days of water curing. The compressive and splitting tensile strength was carried out according to IS 9013-1997 and IS 5816-1999. Ultrasonic pulse velocity test and dynamic modulus of elasticity tests were performed as per IS 13311(part1)-1992 and the Poisson’s ratio was taken as 0.24 ($\mu=0.24$).

RESULTS AND DISCUSSION

3.1 Physical and chemical analyses of OPC and MK:
Physical and chemical properties of the OPC, MK and FA used are presented in Table 3 and 4 respectively. Additionally, the particle size distribution curve for the binding materials is presented in Figure 1. From the particle size distribution curve, it is noted that MK, FA and their combinations are finer than OPC and lesser particle size was observed on FA. The XRD pattern of MK and FA used in this study are shown in Figure 2. From other references, Jutice et al (2007); Parande et al (2011) the FA was mainly in crystalline form, MK is in amorphous form but it slightly deviated from amorphous forms to crystalline form at the angle of 26.8092 °and showing high amount of quartz and silica phase in this pozzolan.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Bulk density in kg/m3</th>
<th>Specific gravity</th>
<th>Fineness passing 45Micron sieve</th>
<th>Blaine specific surface area (m2/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>1.18</td>
<td>1.27</td>
<td>3.13</td>
<td>86 OPC</td>
</tr>
<tr>
<td>MK</td>
<td>0.50</td>
<td>0.52</td>
<td>2.58</td>
<td>99 MK</td>
</tr>
<tr>
<td>FA</td>
<td>0.94</td>
<td>1.20</td>
<td>2.10</td>
<td>95 FA</td>
</tr>
</tbody>
</table>

Table 4: Chemical composition of OPC, MK and FA (%).

<table>
<thead>
<tr>
<th>Material</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>MgO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>Loss on ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC</td>
<td>20.25</td>
<td>5.04</td>
<td>3.16</td>
<td>63.31</td>
<td>4.20</td>
<td>0.08</td>
<td>0.51</td>
<td>3.08</td>
</tr>
<tr>
<td>MK</td>
<td>51.80</td>
<td>43.75</td>
<td>0.82</td>
<td>0.09</td>
<td>0.03</td>
<td>0.07</td>
<td>0.02</td>
<td>0.34</td>
</tr>
<tr>
<td>FA</td>
<td>58.35</td>
<td>27.6</td>
<td>4.82</td>
<td>1.45</td>
<td>1.8</td>
<td>2.46</td>
<td>1.53</td>
<td>3.45</td>
</tr>
</tbody>
</table>

Fig. 1: Particle Distribution curve of OPC, MK, FA and MK+FA.
3.2 Fresh state properties of SCC:

The fresh state properties of SCC containing RHA, MK or a combination of RHA and MK were studied and are presented in Table 5.

From the results, the slump flow values for different concrete mixes were calculated in the range of 610-824 mm. According to values recommended by EFNARC for fresh state properties of SCC as presented (Table 6), all the mixtures examined fall under the categories of slump flow classes 1, 2 and 3 (SF1, SF2 and SF3). These classes in concrete mixes are used to indicate that these mixes are suitable for applications such as deep foundation construction (SF1) and for normal applications such as the building of columns, deep beam etc. (SF2 and SF3). From the results, it can be clearly noted that the slump flow (or filling ability) value gradually reduced with the increments of the replacement level of MK and MK+FA. This condition may be caused by the high reactivity and higher surface area of MK when compared to OPC and FA. It also may be due to the lowest fineness modulus of fine aggregate (FA) (see Table 1). Similar trends in the slump flow values were reported in Eva Vejmelkova (2011), Guneyisi, E and Gesoglu, M (2008).

**Table 5**: Fresh state properties of MK, FA and combination of MK and FA blended SCC.

<table>
<thead>
<tr>
<th>Mix designation</th>
<th>Slump flow in mm</th>
<th>V-Funnel in sec</th>
<th>L-box test, H2/H1</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC(100% OPC)</td>
<td>740</td>
<td>3.9</td>
<td>0.94</td>
</tr>
<tr>
<td>SCC-MK05</td>
<td>735</td>
<td>4.2</td>
<td>0.9</td>
</tr>
<tr>
<td>SCC-MK10</td>
<td>710</td>
<td>4.9</td>
<td>0.85</td>
</tr>
<tr>
<td>SCC-MK15</td>
<td>690</td>
<td>5.8</td>
<td>0.82</td>
</tr>
<tr>
<td>SCC-MK20</td>
<td>678</td>
<td>6.3</td>
<td>0.74</td>
</tr>
<tr>
<td>SCC-MK25</td>
<td>656</td>
<td>7.2</td>
<td>0.63</td>
</tr>
<tr>
<td>SCC-MK30</td>
<td>610</td>
<td>7.9</td>
<td>0.59</td>
</tr>
<tr>
<td>SCC-FA05</td>
<td>725</td>
<td>6</td>
<td>0.9</td>
</tr>
<tr>
<td>SCC-FA10</td>
<td>740</td>
<td>6</td>
<td>0.93</td>
</tr>
<tr>
<td>SCC-FA15</td>
<td>768</td>
<td>5</td>
<td>0.96</td>
</tr>
<tr>
<td>SCC-FA20</td>
<td>785</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>SCC-FA25</td>
<td>786</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>SCC-FA30</td>
<td>824</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>SCC-MK05+FA05</td>
<td>720</td>
<td>4.2</td>
<td>0.91</td>
</tr>
<tr>
<td>SCC-MK10+FA10</td>
<td>710</td>
<td>5</td>
<td>0.85</td>
</tr>
<tr>
<td>SCC-MK15+FA15</td>
<td>695</td>
<td>6</td>
<td>0.79</td>
</tr>
<tr>
<td>SCC-MK20+FA20</td>
<td>640</td>
<td>6</td>
<td>0.71</td>
</tr>
</tbody>
</table>

The V-funnel times for different concrete mixes also appear in Table 5. From the results, it can be noted that the V-funnel times varied in the range of 3.9-7.9 seconds; all concrete mixes could be categorized into the
VF1 class. According to the EFNARC guidelines, a V-funnel time when exceeding 25sec only, it is not recommended (Table 5). From the results, the V-funnel times for all concrete mixes were satisfied this requirement.

Table 6: EFNARC recommended values for fresh state properties of SCC.

<table>
<thead>
<tr>
<th>Slump flow test</th>
<th>Slump Flow (mm)</th>
<th>V-funnel test</th>
<th>V-funnel times (s)</th>
<th>Passing ability Classes</th>
<th>Blocking ratio (H2/H1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SF1</td>
<td>550-650</td>
<td>VF1</td>
<td>≤ 8</td>
<td>PA1</td>
</tr>
<tr>
<td></td>
<td>SF2</td>
<td>660-750</td>
<td>VF2</td>
<td>9-25</td>
<td>PA2</td>
</tr>
<tr>
<td></td>
<td>SF3</td>
<td>760-830</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The L-box test results are also presented in the same Table 5. From the results, the blocking ratio for different mixes varied from 0.59-1. A satisfactory blocking ratio was observed in up to 15% MK, 30% FA, and 20% MK+FA mixes; the value of the ratio for the rest of the mixes was found to be outside the EFNARC-recommended values. Felekoglu et al (2007) concluded that a blocking ratio from 0.6-1 is acceptable for SCC to obtain satisfactory filling ability. In this regard, all concrete mixes were satisfactory (that is, within the prescribed range) except for the 30% MK mix. In summary, all of the mixes exhibited satisfactory fresh state properties (according to the criteria established by EFNARC and Felekoglu et al 2007) except for the 30% MK mixes.

3.3 Mechanical properties of SCC:

From the results, it can be seen that SCC blended with MK and FA have a higher compressive strength than normal SCC (SCC with 100% OPC) (Figure 3). The strength improvement of SCC blended with MK deteriorates with age; a finding that is confirmed by Carlos Fortes Revilla et al (2006). The compressive strength of SCC blended with 15% FA was higher than that of normal SCC. However, the compressive strength of SCC decreased when the quantity of FA was greater than 20%. This may occur due to the increasing workability of the SCC blended with FA, because of the lower surface area of FA than MK and its relative lower water demand. The recent results are also given the similar conclusions (Safiuddin et al (2010); Abhilash et al (2011). This demonstrates the benefit of using FA in combination with MK to produce SCC with a higher cement replacement of around 40% (20% MK + 20% FA). A comparison of the results shows that the compressive strengths improved up to 20% with MK, up to 15% with FA and up to 30% with MK+FA.

Fig. 3: Compressive strength of MK, FA and MK+FA blended SCC.

The similar trend was observed in splitting tensile strength of blended SCC. The splitting tensile strength of MK, FA and combined MK and FA blended SCC are shown in Figure 4. It can be clearly seen that the splitting tensile strength value increases with MK content up to 20%, FA content up to 15% and combined MK and FA up to 30%.The value of splitting tensile strength for MK, FA and combined MK and FA blended SCC mixes is higher than normal SCC, except for 30% FA blended SCC. Ultrasonic pulse velocity (UPV) values for all the mixtures were measured before using the specimen of compressive strength test. UPV values measured for MK, FA and combined blended SCC specimens are presented in Figure 5. It was observed that in comparison with Normal SCC (100%OPC) the UPV values
increases due to the pozzolanic reaction of MK with Ca(OH)\textsubscript{2} and the discontinuity of the porosity network due to the fineness and chemical properties of the material. The mixtures with a higher content of MK and MK+FA (with high amounts of alumina contents) exhibited a much better resistance to ultrasonic wave penetration. From the results, it was also noted that the UPV values for all blended mixes were higher than the unblended SCC except 30% FA blended SCC. BREYSSE (2012) have also confirmed that the UPV of SCC with pozzolanic admixtures is higher than that of unblended SCC.

The past studies showed (Lin et al. 2003) that the pulse of compressional waves through a medium depends on the elastic properties and density of the concrete, therefore, it can be used for determining the properties of concrete. If the density and Poisson ratio are known, dynamic modulus of elasticity (Ed) can be calculated using the expression given below:

\[ E_d = V^2 \rho \frac{(1 + \mu)(1 - 2\mu)}{(1 - \mu)} \]

where \( V \) is the ultrasound pulse velocity, \( \rho \) is the unit weight, and \( \mu \) is the dynamic Poisson’s ratio of concrete. From the previous study (Weiss 2006), for calculating dynamic modulus of elasticity, the Poisson’s ratios were assumed as 0.26 for the substandard concretes, 0.23 for the normal concretes and for this study the Poisson’s ratio was taken as 0.24.

The dynamic modulus of elasticity (DME) values calculated for MK, FA and the combined blended SCC specimens is presented in Figure 6. It can be seen that the DME increased with increasing percentage of MK up to 20%, FA up to 20% and combination of MK and FA up to 30%. This improvement of DME is due to the fact that MK is finer than OPC, FA and produces an additional calcium silicate hydrate (C-S-H) gel. In addition, MK
blocks existing pores and alters pore structure, from the previous study (Luiz et al 2006) confirming that the addition of MK leads to a reduction in the pore space. It is also noted that the DME value for all the blended mixtures were higher than the unblended SCC.

3.4 Relation between UPV and other mechanical properties:

Evaluation of the interrelationship between concrete properties is an important tool to ascertain concrete behaviour through known values. The UPV, as an indicator of structural behaviour of concrete, was chosen. Earlier studies (Shariq et al., 2010) demonstrated that, there is no direct relationship between UPV and other mechanical properties of concrete. However, the UPV of concrete is affected by change in the hardened cement paste, which is influenced by water/cement ratio. It has been noticed and reported, that the UPV wave travels faster through voids containing water as compared to concrete with air-filled voids. Hence, it can be said that the UPV is also may affected by wet condition of concrete. With these above conditions, the UPV test can be used to assess the strength of concrete. It also affects the strength related properties of concrete due to the addition of MK and FA in concrete mixes. Therefore, relationship between compressive strength of concrete containing different percent replacement of MK+FA and UPV has been developed.

The relationship between UPV and other mechanical properties such as compressive strength ($f_c$), splitting tensile strength ($f_t$) and DME ($E_d$) of MK+FA blended SCC are shown in Figure 7, 8 and 9.

This good correlation implies a beneficial synergistic effect of MK+FA replacement on different mechanical related properties. The synergic effect may have occurred because of the good packing behavior of granular materials (MK and FA) in cement, as well as the cement hydration process. In previous studies (Detwiler & Mehta 1989), it has been reported that the particle size of the pozzolanic materials may play an important role in the packing density of the concrete. Since the RHA and MK particle size (see Figure 1) is less...
than that of cement, MK and FA can fill the cement particle gaps effectively. It should also be noted from previous study (Eva et al. 2011), the synergic effect may have occurred due to the effect of SCM’s (MK and FA) on the cement hydration process. With the addition of FA to cement, the hydration is increased at a later stage, whereas in MK blended cement, hydration increases earlier than FA. Therefore, the combination of MK and FA blended cement may increase the hydration at both the early and late stages. This indicates that the combination of MK and FA can have a good synergic effect on the mechanical strength properties of SCC.

**Fig. 8:** Regressions (exponential) between UPV and splitting tensile strength of MK+FA blended SCC.

**Fig. 9:** Regressions (exponential) between UPV and DME of MK+FA blended SCC.

**Conclusion:**

Based on the experimental studies presented in this paper, the following conclusions may be drawn,

1. Up to 40% of OPC (by weight) can be replaced with a combination of MK and FA without any adverse effect on strength and permeability related properties of SCC.
2. Replacement with 30% of MK+FA blended SCC mixes leads to improvement in fresh state and mechanical properties when compared to that of MK, FA and unblended SCC. The improvement is about 31.6% in compressive strength, 26.9% in splitting tensile strength and 25.6% in DME.
3. FA can be considered as a supplementary cementitious material for use in SCC. Although the addition does not significantly improve the mechanical properties it can improve the workability properties compared to that of MK when increasing the replacement level up to about 30%.
4. A strong interrelationships between UPV and mechanical properties of MK+FA blended SCC mixes was observed for compressive strength, splitting tensile strength and DME ($R^2=99.9\%$).
5. The SCC mix with 15% MK and 15% FA showed the best mechanical properties and it may be considered as optimum level of replacement for cement.
REFERENCES


