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# Performance of slag-fly ash based alkali activated concrete for paver applications utilizing powdered waste glass as a binding ingredient

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## Abstract

In the present scenario, there is a huge requirement of quality concrete for paver applications. The production of green and sustainable concrete has become a must to substitute the ordinary Portland cement (OPC) concrete. It is an eminent fact that the manufacture of OPC requires the burning of its raw materials which lead to a huge amount of carbon dioxide liberation; also, it requires a large amount of energy dissipation. The concrete produced using alkali activation has become renowned methods to replace the conventional OPC, which gives an answer to find a way to generate environmentally friendly concrete. In the current study, pavement quality concrete (PQC) is produced using alkali activation. The main focus of the work is to study the effect of powdered glass as a binding ingredient in Alkali-Activated Concrete (AAC) mixes. The alkaline activator used to activate the binder was sodium hydroxide solution dispersed in liquid sodium silicate. The utilization of industrial dissipate materials such as Ground Granulated Blast Furnace Slag (GGBS), fly ash, and waste glass powder was used as the binding ingredients, and stone crusher dust was used as fine aggregates. The experimental investigation showed that a PQC can be easily produced using alkali activation of industrial wastes satisfying its strength requirements. It was behaving better under fatigue, showing its relevance in usage as a pavement construction material.

*Keywords*: Pavement Quality Concrete, GGBS, Glass powder, Alkali activation, strength, Fatigue Performance

## 1. Introduction

The rapid increase in the industrialization and urbanization across the globe has led to the simultaneous increase in the standard of living of the people and an increase in the consumption rate of the people. This high consumption rate has led to a rapid decrease in the natural resources, which is a cause of concern in terms of sustainability of resources, also, the increase in the consumption rate has led to a considerate increase in the waste generated throughout the world. The society that is obsessed with consumption produces a massive amount of waste, this huge amount of waste generated creates a massive pressure to not only manage waste but, to cope with it in a more sustainable manner [1]. As per the general definition of waste, it is any material, element or a by-product which is eliminated or discarded as no longer useful or required after completion of a process. The major by-products are considered to be objectionable and unavoidable in the present society, instead, considering it as a symbol of the inefficiency of the society and as a misallocated resource. More than 1.47 billion tons of wastes are annually generated worldwide out of which only 15% is recycled, and the major part of it is taken to the landfills and becoming one of the reasons for the contaminations [2]. Even with the advancements in the technologies in waste management and treatment, a fundamental sustainable waste management goal such as avoidance and reduction has not been achieved. The industrial waste generation has been continuously increasing and it is expected that the waste generation will continue to increase until it reaches its global peak by the year 2100 unless, sustainable measures are implemented [3].

Among the wastes generated, broken building glass is also a major one. Millions of tons of waste glass are produced all over the world, whose disposal is a great challenge to society. The waste glass, when disposed of in landfills, will be a hazardous activity, as it will not decompose easily. Due to rapid industrialization and urbanization, there is a production of a huge quantity of waste glasses, the utilization of which has become a major challenge to society. Recycling, disposal and decomposing of waste glass cause major problems for municipalities everywhere and this problem can be greatly eliminated by reusing the same. One of the solutions to this problem is the proper usage of waste glass in the production of concrete. Many researchers have studied the use of glass powder in producing concrete and in concrete related applications. The several studies [4-6] has shown that the usage of glass powder

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in Ordinary Portland Cement concrete not only increases the strength but also reduces the unit weight. A study [5] has shown that when the waste glass (both plain and coloured), when finely divided to a micro-sized particle, it is expected to form secondary C-S-H gel due to the formation of pozzolanic reactions when used with a conventional cement binder. They also established the fact that the use of 20% of glass as a replacement to cement will give convincing results. Shayan and Xu [7] studied the utilization of glass as a major ingredient i.e., as aggregates and as a binder material in producing concrete. They also have seen the pozzolanic property in fine glass powder when used in OPC based concrete system, and reduced chloride permeability of concrete which improves the durability concrete. Zidol et al [8] have also shown that the finely ground glass powder has a potential to be used as an alternative supplementary cementitious material (SCM) in producing any concrete of desired strength. Several researchers have studied the effect of powdered waste glass as a binder replacement on the properties of alkali-activated concrete produced using fly ash and GGBS as binders [9-11]. A study by Mithanthaya et al. [9] shown that a cube compressive strength of 32 MPa was achieved for a fly-ash GGBS based concrete with 10% (by weight) powdered waste glass. Thus from many researchers work [12], it is a clear indication that glass powder can be considered for the use in producing alkali activated and conventional concrete as an SCM. However, the use of glass in any type of concrete may boast a danger of Alkali Silica Reaction (ASR). It might be the main issue in concrete containing glass even in the powder form. Tamanna et al (2013) revealed that the use of glass powder as a aggregate in concrete may lead to severe performance issues, where as the use of glass as binding ingredient i.e., in finely ground glass (less than 75 microns size) may not induce any adverse effects in concrete when the aggregates used are non reactive. Thus the use of fine ground glasses as mineral admixture in concrete has shown very less ASR expansion, which further will greatly increase the strength and durability performance [13]. Dhir et al (2009) reported the similar observation, and further proposed that in the concretes where the glass is used as aggregate replacement, the uses of substances like GGBS and metakaolin as mineral admixtures are advised to be used to reduce the expansion problems due to ASR [14]. Thus use of glass in powdered form up-to certain extent, as a cementing ingredient in a GGBS based concrete mix may reduce the problem of ASR.

Similar to glass powder, stone crusher dust (locally called as quarry dust) also posing the disposal problem from the quarries producing crushed stone aggregate. In this place, the availability of good quality, conventional river sand had become very difficult due to the modern regulations on sand mining act of Karnataka State, and it has become very costly too. Many researchers have worked utilizing stone crusher waste i.e., quarry dust in producing good quality concrete. Dehwah [15] stated in his work that quarry dust can be used as a conventional fine aggregate to produce concrete where there is a scarcity of good quality river sand or where the use of natural river sand is not economical. Prakash and Rao [16] stated that a design concrete strength can be easily obtained when the river sand is replaced up to 40% by quarry dust. In that work, the quarry dust utilization level-up to 40% was studied for an M-20, M-30 and M-40 grade of concrete and reasonable results were obtained for various ages up to 60 days. Devi and K. Kannan [17] revealed that the replacement of quarry dust increases the strength of OPC based concrete and the use of corrosion inhibitors in the concrete will ensure the greater resistance to permeability, corrosion, and adverse action of environment making the concrete more durable. Thus in our study, an attempt is also made to fully replace the conventional river sand by the waste stone crusher dust in producing concrete, so that disposal problem of quarry dust can be minimized.

Many industries are producing by-product materials which are generally considered as waste and useless materials and their disposal is a problem. Fly-ash is one such by-product obtained by burning of coal in thermal power plants. Near to our Institution, there is a thermal power plant (1200 MW capacity) which produces around 300 tonnes of fly ash per day, out of which 80% is sucked by electrostatic precipitator, which may be utilized for the production of concrete. If this fly-ash is not utilized, it would lead to an environmental toxic waste, which may contaminate the landfill and water.

The Blast Furnace Slag is the major by-products produced during the production of steel. The blast furnace slag is available in the form of fine powder in the market, called Ground Granulated Blast Furnace Slag (GGBS) and is cheaper than Portland cement. The annual production of GGBFS is estimated at 530 million tons, of which 65% is utilized [18,19]; this implies that more waste can be utilized to produce concrete.

The Ordinary Portland Cement is a well known major binder material used in producing conventional cement concrete in India. The production of Portland cement produces a huge quantum of carbon dioxide ($CO_2$) during its manufacturing. Usage of cement in various material leads to an increase in the greenhouse effect and global warming. It is a well-known fact that during the production of each metric ton of OPC results in roughly 1000 kg of $CO_2$ released into the atmosphere, and studies have shown that worldwide production of cement causes 6–7% of global greenhouse gas emissions. In addition, the production of OPC consumes an enormous amount of energy. It consumes about 4-7 MJ of fossil fuel energy per kilogram [20,21].

Hence there is a burning challenge to replace this conventional cement concrete with other alternative concrete which is more eco-friendly and more economical, without compromising on the mechanical requirements of concrete. Usage of SCMs (such as fly ash, GGBS etc.) as a partial replacement to conventional Portland Cement based concrete (called as blended concretes) is one act of producing a more sustainable concrete than direct use of OPC concrete. Another alternative is avoiding the use of OPC cement in producing concrete. One such alternative is the use of alkali-activated binder in producing concrete [21]**.** On alkali-activated cement and concretes, there are many research articles published by Prof. Sanjayan from 1997 till date are showing the significant potential in such concretes to be used as an effective replacement for OPC based concrete. These alkali activated concretes have been found to have some superior properties as compared to OPC concrete, namely, low heat of hydration, high early strength, and excellent durability in the aggressive environment [22]**.**

Thus by considering all the above facts, an attempt is made to solve the local problem of disposal of industrial wastes such as glass powder, fly ash, GGBS, and quarry dust by utilizing the same in a hunk of non-conventional-alkali activated cement concrete, without compromising the strength and durability requirements.

In the present study, the mechanical properties of the newly produced concrete are assessed. The design mix is prepared to produce concrete for the satisfactory application as a rigid pavement surface construction material. The scanning electron microscope imaging of the binder ingredients is carried out to study their microstructure. The compressive strength on standard cube specimen is studied for the various trail mixes and an optimum binder dosage is obtained. The study is also done to evaluate the indirect tensile strength and static flexural strength for various dosages of alkaline activator. The dynamic flexural fatigue performance of the AAC prism specimens was also examined.

## 2. Materials and methodology

The materials used to produce alkali-activated concrete are discussed in the following section. The Ground Granulated Blast Furnace Slag (GGBS) used for this experimental work had a specific gravity of 2.89, and fineness in the range of 400-600 m$^2$/kg. The ASTM Class F type fly-ash was procured from the local thermal power plant. The material was greyish white in colour had a specific surface area in the range 290-350 m$^2$/kg, the specific gravity of 2.16. A finely grounded glass was also used in the present investigation as a binding ingredient. The locally available waste building glass collected, cleaned and then powdered. The resultant glass powder was fair in colour, which had a specific gravity of 2.45 and the mineral composition of the binding ingredients is shown in the Table 1. The locally available stone quarry dust passing 4.75 mm IS sieve which is classified as zone II as per IS-383 [23] is used for the investigation. The locally available crushed stones passing through 20 mm IS sieve is used as the coarse aggregates. The material properties of the aggregate used are shown in Table 2. The aggregates used were satisfying all the requirements as per Indian Standards.

The alkaline solution consists of solid sodium hydroxide crystals (NaOH) with 98% purity and liquid Sodium silicate solution. Both the ingredients are purchased from local commercial suppliers. The alkaline solution was prepared by preparing the aqueous solution consisting of the required amount of NaOH crystals in sodium silicate solution and water. The alkali deliberation of the activator is an elementary need for improving the perfunctory properties of binding ingredients i.e., GGBS, fly-ash, and glass powder.

Flexural strength is the basic criteria for designing rigid pavements. As per IRC: 15-2011, the minimum flexural strength required for any pavement is 4.5MPa i.e., a minimum compressive strength of 40 MPa(M-40 grade) is suggested. In this study, a PQC mix of grade M-45 was prepared using the conventional Indian method using IS-10262 2009 [24] for a target slump value of 0 to 25, and the same was modified according to the available literature to obtain the GGBS-Flyash based mix design for AAC [25]. From the literature, for the mix design, the amount of activator used for the current work was 4% by weight of the total binding material in the mix, which was kept constant throughout the work. The activator modulus was prepared referring to the literature [25,26]. Further, the mix was prepared for AAC with varied activator modulus ranging from 0.50 till 2.0- varied at an interval of 0.25. The water-binder ratio was maintained at 0.40. The initial obtained mix design for the mix without using glass powder in the design for all the activator modulus ranging from 0.5 to 2.0 is shown in the Table 3.

Table 1
Mineral composition of binding ingredients.

| GGBS | | Fly ash | | Glass powder | |
|---|---|---|---|---|---|
| CaO | 30-45% | $SiO_2$ | 48-58% | $SiO_2$ | 71-83% |
| $SiO_2$ | 17-38% | $Al_2O_3$ | 25-33% | Na2O | 9-15% |
| $Al_2O_3$ | 15-25% | $Fe_2O_3$ | 13-22% | CaO | 5-10% |
| $Fe_2O_3$ | 0.5-2% | CaO | 6-10% | MgO | 1-6% |
| MgO | 4.0-17% | LOI | 5-6% | K2O | 0-1% |
| $MnO_2$ | 1.0-5% | Others | 0-7% | Others | 0-2% |

Table 2
Physical properties of coarse aggregates.

| Property | Coarse aggregates | Fine aggregates | Test method (IS-Code) |
|---|---|---|---|
| Specific gravity | 2.72 | 2.61 | IS:2386-Part 3 (1963) |
| Aggregate impact value | 21.5% | - | IS:2386-Part 4 (1963) |
| Aggregate crushin value | 22.0% | - | IS:2386-Part 4 (1963) |
| Los Angeles abrasion value | 24.0% | - | IS:2386-Part 4 (1963) |
| Water absorption | 0.90% | 3.94% | IS:2386-Part 3 (1963) |
| Bulk density | | | |
| (i) dry loose state | 1498 kg/m$^3$ | 1437 kg/m$^3$ | IS:2386-Part 3 |
| (ii) dry compact state | 1655 kg/m$^3$ | 1568 kg/m$^3$ | (1963) |
| Fineness modulus | 7.24 | 3.18 | IS:2386-Part 3 (1963) |

The design mix in the company of glass powder with the fly-ash content for the mix with a modular ratio of 1.25 is shown in Table 4. M-0 indicates mix with 0% glass powder and M-25 indicates the mix with 25% of glass powder-replaces with respect to the fly-ash content by weight. The GGBS content was kept constant at 75% by weight in all the mixes.

The calculated amount of fly ash, GGBS, glass powder, and aggregates are thoroughly dry mixed in a blender. Then alkalineactivator is added to the dry mix, which is then mixed together to form a uniform mixture. The constituents are mixed meticulously until a homogeneous consistency was attained. Standard test specimens were cast for a study of the performance. All the cast specimens were air cured in laboratory condition prior to testing. All the castings are done at the new research laboratory.

Table 3
Initial design mix for various modular ratio from 0.5 to 2.0 in kg per cubic meter.

| Modular Ratio $M_s$ | GGBS | Fly Ash | Water | Alkaline solution | Coarse Aggregates | Fine aggregates |
|---|---|---|---|---|---|---|
| 0.5 | 330 | 110 | 88 | 118.365 | 1119.067 | 678.29 |
| 0.75 | 330 | 110 | 88 | 122.192 | 1113.71 | 675.04 |
| 1.0 | 330 | 110 | 88 | 126.02 | 1108.35 | 671.79 |
| 1.25 | 330 | 110 | 88 | 129.847 | 1102.99 | 668.54 |
| 1.5 | 330 | 110 | 88 | 133.675 | 1097.63 | 665.29 |
| 1.75 | 330 | 110 | 88 | 137.502 | 1092.27 | 662.05 |
| 2.0 | 330 | 110 | 88 | 141.33 | 1086.91 | 658.80 |

Table 4
Design mix of 1.25 modular ratio for varied glass powder content in kg per cubic meter.

| Mix-ID | GGBS | Fly ash | Glass powder | Water | Alkaline solution | Coarse aggregates | Fine aggregates |
|---|---|---|---|---|---|---|---|
| M-0 | 330 | 110 | 0 | 88 | 129.8 | 1103.0 | 668.5 |
| M-5 | 330 | 88 | 22 | 88 | 129.8 | 1103.8 | 669.1 |
| M-10 | 330 | 66 | 44 | 88 | 129.8 | 1104.7 | 669.6 |
| M-15 | 330 | 44 | 66 | 88 | 129.8 | 1105.3 | 670.1 |
| M-20 | 330 | 22 | 88 | 88 | 129.8 | 1106.4 | 670.6 |
| M-25 | 330 | 0 | 110 | 88 | 129.8 | 1107.2 | 671.1 |

in the Civil Engineering Department of NMAMIT Nitte The testing of the specimens was done in the department concrete laboratory. In the present investigation, the compressive strength on cube and cylinders, the split tensile strength on cylinder specimen, the flexural strength test on reinforced and plain concrete prism specimens produced using alkali-activated cement based concrete as per standard Indian code specifications [27]. The investigation is further continued to study the flexural fatigue test on GGBS-flyash-glass powder based concrete and the results are derived. The microstructural imaging of binding ingredients was done using scanning electron microscopy (SEM). The SEM imaging was done at the National Institute of Technology (NIT) Surathkal- Karnataka- utilizing the SEM facility available in the Department of Metallurgy. The SEM images showing the surface appearance of the binding ingredients used in the study were shown in Figs. 1(a) to 1(c).

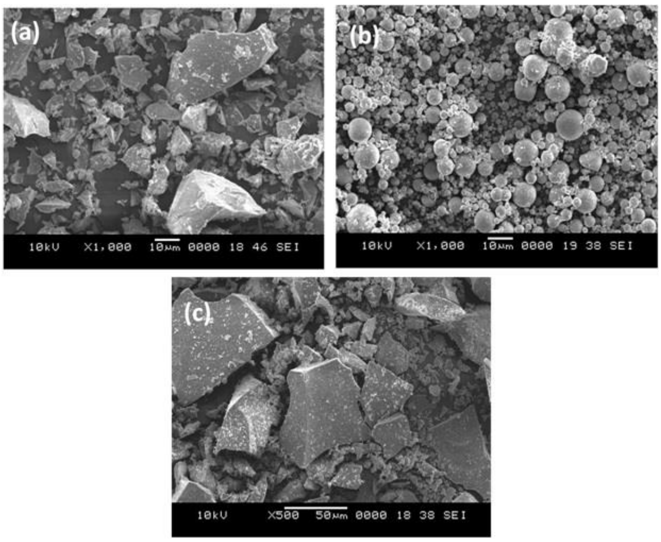

Fig. 1. SEM micrographs of (a) GGBS (b) fly ash (c) glass powder.

## 3. Test outcomes and discussion

### *3.1. Workability, unit weight and compressive strength*

The mix was prepared to show design workability of 0-25mm range (slump value). The slump value of casted alkali-activated concrete mix was observed to be within the design range i.e., 0 to 25 mm slump, showing the attainment of target slump value when tested using a standard slump-cone according to Indian Standards [28]. The crushing strength of the mixes was performed on 100mmX100mmX100mm concrete cubes as per IS:516 specifications [27]. From the initial mix design (shown in Table 3), the 28-day cube compressive strength was only studied. The results indicated that a maximum 28-day compressive strength of 62 MPa was observed for the mix with Ms=1.25 (i.e., corresponding to M-0 mix). Further, for the mix of modular ratio-Ms=1.25, the variation of fly-ash was done with glass powder up to 25% (in the interval of 5%). The mix proportion details were shown in Table 4. The density (i.e., unit weight at 28 days) and the compressive strength for this GGBS-fly-ash and glass powder based alkali-activated concrete mixes, reported an average of 3 representative sample readings were shown in Table 5. The deviation of the results are in between 4.90% to 9.20% for compressive strength test results. There was a marginal increase in slump value as there was an increment in activator modulus. With the increase in glass powder content, there was a slight decrease in the slump value- this may be due to the coarser size of glass powder while compared with the particles of fly-ash. The unit weight of all mixes was observed to be similar to that of conventional OPC based concrete; the similar observations were reported by several researchers [29,30]. The results clearly indicate that a maximum 28 days strength of 68 MPa was observed for M-15 mix. The results indicated that, all mixes have achieved the target design strength; and, for all alkali-activated concrete mixes there is an early gain in strength to an age of 28 days and thereafter it shows a minimal or no significant increase in its strength up to 180 days of air curing; the results are in line with the literature

Table 5
Compressive strength and unit weight of AAC mixes.

| Mix-ID | Density at 28 days (kg/ m$^3$) | Compressive strength (MPa) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 3 days | 7days | 14 days | 28 days | 56 days | 90 days | 180 days |
| M-0 | 2389 | 18.0 | 25.2 | 47.1 | 62.3 | 67.5 | 68.7 | 69.1 |
| M-5 | 2412 | 16.2 | 23.4 | 48.6 | 58.1 | 60.8 | 61.0 | 61.3 |
| M-10 | 2403 | 19.0 | 27.6 | 39.0 | 60.3 | 60.2 | 62.8 | 63.2 |
| M-15 | 2415 | 22.1 | 39.7 | 51.2 | 68.1 | 71.2 | 71.7 | 72.3 |
| M-20 | 2398 | 20.0 | 31.8 | 43.7 | 59.0 | 60.8 | 62.0 | 62.7 |
| M-25 | 2392 | 14.3 | 26.2 | 41.0 | 57.3 | 57.9 | 58.4 | 58.0 |

[25,26,29]. The high early strength in AAC mixes was mainly due to the presence of GGBS, which experiences a quicker hydration-reaction in the attendance of powerful alkaline medium as a contrast to the pace of hydration response taking place in Portland concrete mixes [31,32]. The maximum strength at 15% replacement of glass powder may be due to the pozzolanic reactivity of powdered glass up to certain limits while it has been replaced as a binding ingredient in cementing mixtures while producing concrete mixes [6,7,9].

### 3.2. *Tensile strength and elasticity modulus*

The tensile strength of AAC mixes was evaluated in-terms of and static flexural strength test, and split-tensile strength test, conducted according to IS:516 [27] and IS:5816 [33] respectively. Both the tests were conducted for 7, 28 and 90 days of air curing, for the mix proportion details shown in table 4. The test results were indicated in table 6, the standard deviation of the results observed sre 3.3% to 5.0% for split tensile and 4.5% to 7.7% for flexural strength tests; which is very well within the maximum allowable deviations limit of 15% [34].

From the test results, it could be seen that there is a marginal increase in both 28-day split-tensile strength and static flexural strength values for all the AAC mixes from M-0 to M-25. M-15 mix had attained the maximum 90-day flexural strength value of 6.91 MPa, which was about marginal 6.0% higher than the reference AAC i.e. M-0 mix. Similarly, the split-tensile strength value of M-15 mix was 4.91 MPa, which was found to be about marginal 2.0% higher than the reference AAC mix. The higher tensile strength of AAC mixes may be due to the development of distinctive microstructure and subsistence of well-built aggregate-paste interface on account of the presence of dense interfacial transition zone in alkali-activated binders [35].

The determination of elastic modulus is done for AAC mixes at the age of 28 days in accordance with IS:516 [27]. The results of elasticity modulus conducted on the AAC samples of 150mm diameter and 300 mm height cylinders at 28 days are depicted in table 6. The results indicate that there is only a 3% marginal increase of modulus value of M-15 mix when compared with that of the reference M-0 mix. Thus overall, while compared with the elastic modulus of presently studied AAC mixes, it can be stated that there will not be any kind of difference when compared with conventional GGBS-Flyash based AAC mixes(M-0) while compared with that of the GGBS-glass powder based AAC mixes (M-5 to M-25).

### 3.3. *Volume of permeable voids (VPV) and water absorption*

The tests for VPV and water absorption were conducted at 28 days of air-curing in accordance with ASTM specifications [36]. Figs. 2 and 3 indicate the VPV and water absorption of AAC mixes at 28 days of air-curing. The total porosity and water absorption marginally decrease with the increase in glass powder content. This may be due to the negligible water absorption capacity and smooth surface texture of glass powder, which was found earlier by the researchers [6,37]. At a lower level of replacement of fly-ash with powdered glass, the VPV values were almost near to that of reference AAC -0 mix. As the dosage of glass powder increases, there was a decrease in porosity of the mix. This probably may due to the existence of very refined closed aperture structure in the AAC samples which hamper the water from entering into the concrete structure [38,39].

Table 6
Tensile properties of AAC mixes.

| Mix-ID | Elastic modulus (GPa) | Tensile strength (MPa) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Flexural strength (MPa) | | | Split-tensile strength (MPa) | | |
| | | 7 days | 28 days | 90 days | 7 days | 28 days | 90 days |
| M-0 | 33.1 | 4.82 | 5.74 | 6.54 | 2.3 | 4.24 | 4.81 |
| M-5 | 32.3 | 3.68 | 5.12 | 5.92 | 1.93 | 4.21 | 4.35 |
| M-10 | 33.1 | 3.79 | 5.34 | 6.21 | 2.12 | 4.37 | 4.51 |
| M-15 | 34.2 | 3.81 | 5.8 | 6.91 | 2.31 | 4.81 | 4.91 |
| M-20 | 33.7 | 3.82 | 5.38 | 6.12 | 2.44 | 4.39 | 4.79 |
| M-25 | 31 | 3.44 | 5.19 | 5.97 | 2.19 | 4.28 | 4.37 |

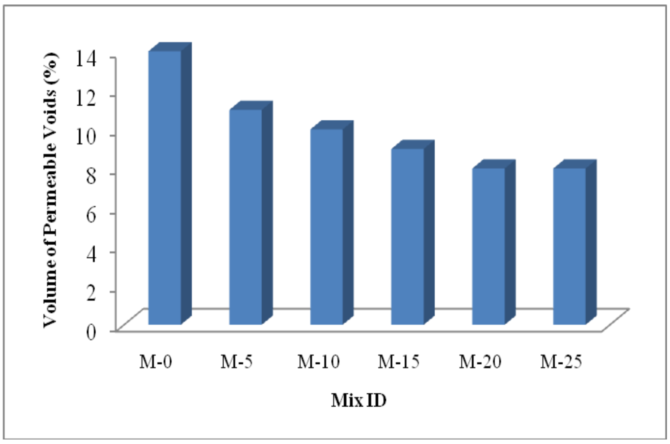

Fig 2. Volume of permeable voids for AAC mixes.

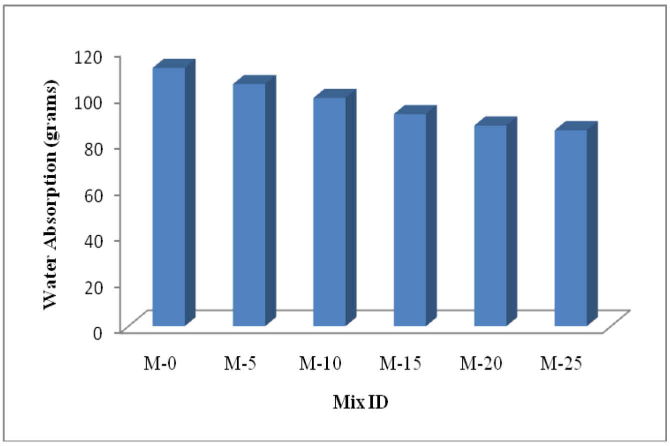

Fig. 3. Water absorption for AAC mixes.

### 3.4. *Flexural fatigue test*

Fatigue malfunction is one of the most important failures in the structure like cement concrete pavements and takes place over a long phase of time due to frequent movement of heavy traffic vehicles and elevated intensity vehicular movements. The fatigue failures in concrete pavements occur at the repetitive or cyclic loads in such a manner that whose peak stress values are considerably less than the safe load estimated in static flexural strength. The fatigue failure in concrete structures causes progressive, localized and permanent damage due to dynamic or moving or cyclic loads [40].

For the current investigation, the loads are applied in repeated cycles to cause the failure of concrete beams at stress less than the maximum value of the strength of beams. The AAC prism specimens of size 100mmx100mmx500mm were cast and tested after 28 days of air curing. The experimental set-up used for this study was from BMS College of Engineering, Bangalore. The beams were loaded using a constant amplitude half sinusoidal wave. The load cells apply the load at the rate of 6 cycles per second (frequency= 6Hz) with pressure maintaining at 40 bars. The failure criterion is either beam should deflect 3mm or it breaks for repeated loading. (Two vertical Linear Variable Differential Transformers are used to measure the deflection).

The allowable number of repetitions of load up to fatigue failure or ‘fatigue life’ of the concrete prism of best combination mixes have determined for various values of stress ratios (S) between 0.65 and 0.85. The fatigue life (N) after the failure of the beam is noted. A graph between ‘S’ and ‘N’ is plotted to obtain ‘S-N curve’ or Wohler curve method, which was found to be an effective method to understand the concrete fatigue failure behaviour [25,29,40]. In the present investigations, the flexural fatigue test on various selected AAC mixes (from M-0, M-15 and M-25) were conducted on standard beam specimen. The load amplitude applied to the specimen is represented in terms of ‘Stress ratio’. The beams are tested for stress ratios like 0.65, 0.7, 0.75, 0.8 and 0.85. The load amplitude is maintained constant for a particular beam at a given stress ratio. The fatigue life of all the mixes is shown in table 7. The last row of Table 7 gives the standard values of an allowable number of repetitions as per IRC:58-2015 [41] guidelines. The S-N Curve of the corresponding mixes were indicated in Figs. 4 to 6.

The fatigue results indicate that all the AAC mixes displayed a higher resistance to fatigue failure as compared with the allowable fatigue repetitions as per the standards. This may be due to the highly dense interfacial transition zone between the paste and the aggregate occurring in alkali-activated binders [35]. Further, the inclusion of glass powder in AAC mixes have shown an increment of the fatigue cycles till 15% replacement with fly-ash and thereby it leads to a reduction in the repetitions when compared with 25% mix. From Table 7, it can be also noted that at 25% dosage of glass powder (M-25) lead to comparatively fatigue less performance while compared with M-15 and M-0. Hence it can be stated that M-15 mix is the best one, and dosage of the glass powder more than 25% is not of much significance. Further, Table 8 shows the statistical relationship i.e., the correlation equations between fatigue cycles to failure (N) and stress ratio (S) generated from S-N curves, which may be utilized to estimate the fatigue cycles for similar mixes at any level of stress.

It can be perceived that the AAC samples can resist more repetitions when the stress-levels are lesser (i.e., 0.75, 0.70, 0.65); on the other hand, at a higher stress intensity, the samples experience failure at a relatively smaller number of repetitions. All the samples failed in the centre one-third span when observed visually. This observation was in line with the literature [29]. As observed from Table 8, the statistical correlation coefficients fall in the range 0.91–0.94 for all AAC mixes representing the statistical significance of the fatigue data.

Table 7
Fatigue life of AAC specimens.

| Mix ID | Stress level | | | | |
|---|---|---|---|---|---|
| | 0.65 | 0.70 | 0.75 | 0.80 | 0.85 |
| M-0 | >250000 | 1,79,076 | 89,674 | 18,660 | 940 |
| M-15 | >250000 | 2,10,966 | 87,640 | 28,660 | 1,872 |
| M-25 | >250000 | 1,61,593 | 73,568 | 14,992 | 824 |
| Standard allowable value of repetitions as per IRC | 7700 | 1970 | 477 | 119 | 30 |

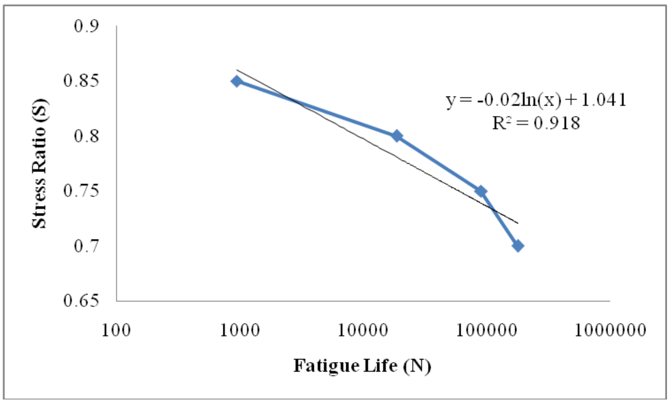

Fig. 4. S-N curve for M-0 mix.

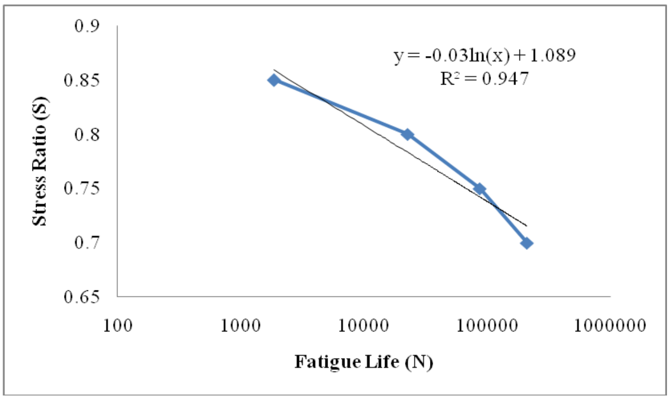

Fig. 5. S-N curve for M-15 mix (optimum).

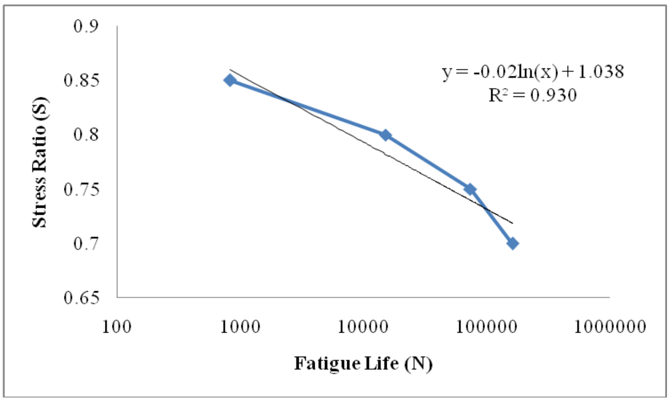

Fig. 6. S-N curve for M-25 mix.

Table 8
Relationship between fatigue life (N) and stress ratio (S).

| Mix ID | Equations | $R^2$ value |
|---|---|---|
| M-0 | $\ln (N) = 52.05 - S/0.02$ | 0.918 |
| M-15 | $\ln (N) = 36.3 - S/0.03$ | 0.947 |
| M-25 | $\ln (N) = 51.90 - S/0.02$ | 0.930 |

## 4. Conclusions

The investigations were made to obtain a pavement quality concrete using alkali activation of binding ingredients. The main focus was done to investigate the utilization of glass powder in producing GGBS-flyash based AAC. Initially, the standard modular ratio of 1.25 is obtained based on 28 day compressive strength values of initially designed GGBS-Flyash based AAC without glass powder. This standard modular ratio of 1.25 was used for preparing further design mixes incorporating glass powder. In this section, key conclusions drawn from this GGBS-Flyash-glass powder based AAC mixes are summarized out here.

1. The unit weight of all the studied mixes was showing the values similar to that of the conventional OPC concrete and the limits are within the Indian standard code provisions. However, there was a slight increase in the unit weight value as the percentage of glass powder in the mix increased. The workability of all the AAC mixes was within 0-25 mm, since it was a PQC mix proportions design.
2. The compressive strength results indicate that there is an early gain in strength value was observed in all the mixes. The strength development beyond 28 days is not of that much significance. The maximum 28-day compressive strength was obtained for the AAC mix containing 15% glass powder (M-15 mix).
3. In-line with the compressive strength results, the maximum static flexural strength, spilt-tensile strength and the elastic modulus were obtained for the AAC mix containing 15% glass powder (M-15 mix).
4. The volume of permeable voids reduces as the percentage of powdered glass dosage increases, which may be due to the presence of the formation of a dense microstructure in AAC due to the induction of powdered glass. In this admiration, the microstructural study of hardened concrete paste is needed for enhanced recognizing. The water absorption results will also showcase a similar trend.
5. Dynamic flexural fatigue test results indicate that all the AAC mixes performed in a satisfactory manner satisfying the standard requirements. The incorporation of glass powder up to 15% has shown a very good fatigue performance, indicating greater resistance to the cyclic load applied while compared with M-0 and M-25 mixes. The S-N curve derived and the correlation equations with good R-square value may be used for extrapolating the number of repetitions at any other stress levels.

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