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Performance evaluation of cement stabilized fly ash–GBFS mixes as a highway construction material

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Abstract

Fly ash and granulated blast furnace slag (GBFS) are major by-products of thermal and steel plants, respectively. These materials often cause disposal problems and environmental pollution. Detailed laboratory investigations were carried out on cement stabilized fly ash–(GBFS) mixes in order to find out its suitability for road embankments, and for base and sub-base courses of highway pavements. Proctor compaction test, unconfined compressive strength (UCS) test and California Bearing Ratio (CBR) test were conducted on cement stabilized fly ash–GBFS mixes as per the Indian Standard Code of Practice. Cement content in the mix was varied from 0% to 8% at 2% intervals, whereas the slag content was varied as 0%, 10%, 20%, 30% and 40%. Test results show that an increase of either cement or GBFS content in the mixture, results in increase of maximum dry density (MDD) and decrease of optimum moisture content (OMC) of the compacted mixture. The MDD of the cement stabilized fly ash–GBFS mixture is comparably lower than that of similarly graded natural inorganic soil of sand to silt size. This is advantageous in constructing lightweight embankments over soft, compressible soils. An increase in percentage of cement in the fly ash–GBFS mix increases enormously the CBR value. Also an increase of the amount of GBFS in the fly ash sample with fixed cement content improves the CBR value of the stabilized mix. In the present study, the maximum CBR value of compacted fly ash–GBFS–cement (52:40:8) mixture obtained was 105%, indicating its suitability for use in base and sub-base courses in highway pavements with proper combinations of raw materials.

1. Introduction

Development of adequate network of roads is of vital importance in the socio-economic development of a country. The quantum of materials required for the construction is usually huge. Soil is the cheapest available material utilized by man for various construction-related purposes. The scarcity of suitable graded soil at construction sites has forced engineers and scientists to utilize waste products of industries that either degrade the environment or pose problems for their disposal. In this connection, utilisation of by-products like fly ash and granulated blast furnace slag, as suitable ingredients for geotechnical construction, needs special attention. Most of the thermal power plants in India are coal based, and it is estimated that the generation of fly ash from coal-fired generation units will reach 170 million tonnes per annum by 2012 AD. At present, as per the report of the Fly Ash Utilisation Programme (FAUP), out of the huge quantity of fly ash produced, only about 35% finds its use in commercial applications such as mass concrete, asphalt paving filler, lightweight aggregate, stabilizer to road bases, raw material for concrete, additives to soil, construction of bricks, mining stowing etc. The remainder is a waste requiring large disposal areas, causing a huge capital loss to power plants and simultaneously causing an ecological imbalance and related environmental problems (Dhir, 2005).

Granulated blast furnace slag (GBFS) is a by-product obtained in the manufacture of pig iron in the blast furnace

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and is formed by the combination of iron ore with limestone flux. If the molten slag is cooled and solidified by rapid water quenching to a glassy state, little or no crystallization occurs. This process results in the formation of sand size fragments, usually with some friable clinker-like material known as granulated blast furnace slag. The physical structure and gradation of granulated slag depend on the chemical composition of the slag, its temperature at the time of water quenching and the method of production. India is the largest producer of iron ore; about 15 million tonnes of slag are produced annually from steel plants. The main composition of slag is lime, alumina, silica and magnesia, whose percentages may vary depending on the nature of iron ore, the composition of limestone flux and the kind of iron being produced. The physical properties and chemical composition of fly ash and GBFS used in the present investigation are given in Tables 1 and 2, respectively. This shows that GBFS contains free calcium oxide, reactive silica and alumina, which can be successfully utilized in pozzolanic reaction (Singh et al., 1996).

Fly ash is recycled as a construction material to take advantage of its pozzolanic characteristics. Pozzolanic or self-hardening properties depend on the availability of lime in fly ash. If there is insufficient bonding between the particles of fly ash due to lack of pozzolanic reaction, as in the case of low lime fly ash, it will be in a very loose state creating problems related to leaching and dust emissions. Numerous studies on applications of fly ash as bulk fill material are available (Raymond, 1958; DiGioia and Nuzzo, 1972; Gray and Lin, 1972), which demonstrated the possibility of utilizing huge amounts of fly ash in the construction of embankments, dykes and road subgrade.

Poran and Ahtchi-Ali (1989) investigated the suitability of solid waste incinerator fly ash as construction material in road and sub-base construction on stabilizing the ash with 5% and 10% of lime or cement. Reported research findings of Nicholson et al. (1994) have shown that lime–fly ash admixture stabilization can be used in a variety of construction applications such as fills and pavements.

Table 1
Physical properties of fly ash and GBFS

Physical parameters	Fly ash	GBFS
Colour	Blackish green	Brown
Shape	Rounded	Sub-rounded to angular
Grain size distribution (%)		
Silt & clay	13	1.5
Fine sand	87	16
Medium sand	0	72.5
Coarse sand	0	10
Uniformity coefficient ($C_U = D_{60}/D_{10}$)	2.13	3.85
Coefficient of curvature, $C_C = (D_{30})^2/(D_{10} \times D_{60})$	1.12	1.43
Specific gravity	2.15	2.61
Plasticity index	Non-plastic	Non-plastic

Note: D_{10}, D_{30} or D_{60} represent the sizes, in mm, such that 10%, 30% or 60% (by weight) of the particles are finer than these sizes, respectively.

Table 2
Chemical composition of raw materials in percentage (by weight)

Constituent	Cement	Fly ash	GBFS
SiO_2	20.22	58.95	33.4
Al_2O_3	4.84	29.33	18.2
CaO	62.48	1.05	35.3
Fe_2O_3/FeO	3.36	5.6	1.2
MgO	3.17	1.25	6.5
TiO_2	–	1.7	–
P_2O_5	–	0.25	–
K_2O	0.61	0.85	–
Na_2O	0.66	0.61	–
SO_3	2.81	0.41	–
MnO	–	–	0.75
CaS	–	–	0.5
LOI	1.85	–	–
Others	–	–	4.15

Class F fly ash is the least commonly used ash, mainly due to its lack of self-cementitious properties. It consists of siliceous and aluminous materials (pozzolans) that lack cementitious value by themselves, but chemically react with calcium oxide in the presence of moisture to form cementitious compounds (Cockrell and Leonard, 1970). Bergeson and Barnes (1998) developed guidelines for determining the structural layer coefficient for the base layer of the flexible pavements. Parsons and Milburn (2003) conducted a series of tests to evaluate the relative performance of common additives (lime and cement) to Class C fly ash.

Considerable research has been done to utilise the coal ash and slag in different fields of engineering. Table 3 gives the statistics on utilisation of coal ash and slag. However, no attempt has been made to evaluate the geotechnical properties such as compaction characteristics; UCS value and CBR value of cement stabilized fly ash–GBFS mixes. This paper reports the geotechnical properties of fly ash–GBFS–cement mixes and its suitability in highway construction.

2. Material characterizations and methodology

2.1. Raw materials

Fly ash and granulated blast furnace slag used in this investigation were collected in gunny bags from the captive power plant-II and slag granulation unit of Rourkela Steel Plant. These raw materials were mixed thoroughly and sun-dried. The average moisture content of the sun-dried raw materials was determined, which were separately stored in covered galvanised iron tanks for future use. Likewise ordinary Portland cement of grade 42 was procured from Orissa Cement Ltd., Rajgangpur. The specific gravity of fly ash and GBFS were determined as per IS: 2720 part-III, Section-1, 1980. The particle size distribution of fly

Table 3
Statistics of use of slag and coal ash

Countries	Blast furnace slag		Steel slag		Coal bottom ash		Coal fly ash	
	Production (million tons)	Utilisation (%)	Production (million tons)	Utilisation (%)	Production (million tons)	Utilisation (%)	Production (million tons)	Utilisation (%)
USA	14	90	–	–	14	31	53.5	27
Sweden	1.1	45	0.22	100	–	–	–	–
Germany	9.2	100	5.3	92	3.1	97	3.4	88
Denmark	–	–	0.066	100	2.0	100	1.17	100
Netherlands	1.32	100	0.55	100	0.09	100	0.94	100
India	15	55	–	–	–	–	110	35

ash and GBFS were determined as per IS: 2720 part-IV, 1985 and is shown in Fig. 1. The particle size distribution curve gives an idea about the size range and distribution of particles in the sample. It is found that almost all of the fly ash particles are of fine sand to silt size, whereas most of the GBFS particles are of medium sand size. Uniformity coefficient and coefficient of curvature are measures of the distribution of different size particles in the sample. Uniformity coefficient and coefficient of curvature for fly ash are found to be 2.13 and 1.12, respectively, indicating fly ash is uniformly graded. Similarly, the uniformity coefficient and coefficient of curvature for GBFS are 3.85 and 1.43, respectively, indicating that it is a well-graded material within its range having grain size ranging from silt to coarse sand.

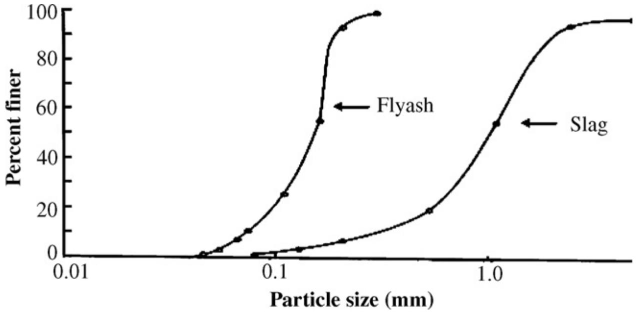

Fig. 1. Particle size distribution curves for fly ash and slag.

2.2. Methodology

The engineering properties such as compaction characteristics, unconfined compressive strength and California bearing ratio (CBR) value of different mixes of fly ash–GBFS–cement were evaluated to examine the suitability of these materials in highway construction. Table 4 gives the details of fly ash–GBFS–cement mixes that were used in the experimental programme. During the experimentation, the required quantities of various materials were collected and the test specimens were prepared as per the requirements of the specific tests.

2.2.1. Proctor compaction test

The moisture content versus dry density relationship for different mixes of fly ash–GBFS–cement was determined by using the light compaction test as per IS: 4332 (Part-3), 1967. The moisture content of compacted mixture was determined as per IS: 4332 (Part-2), 1967. From the dry density and moisture content relationship, the optimum moisture content (OMC) and maximum dry density (MDD) were calculated.

2.2.2. Unconfined compressive strength test

Unconfined compressive strength of various combinations of fly ash, slag and cement were determined as per IS: 4332 (Part-5), 1970. The specimens were prepared at their respective OMC and MDD by applying static compressive force in a constant volume sampler. The

Table 4
Details of fly ash–GBFS–cement mixes used in the experimental programme

Sl. no	Cement (%)	GBFS (%)	Fly ash (%)	Sl. no	Cement (%)	GBFS (%)	Fly ash (%)
1	0	0	100	14	4	30	66
2	0	10	90	15	4	40	56
3	0	20	80	16	6	0	94
4	0	30	70	17	6	10	84
5	0	40	60	18	6	20	74
6	2	0	98	19	6	30	64
7	2	10	88	20	6	40	54
8	2	20	78	21	8	0	92
9	2	30	68	22	8	10	82
10	2	40	58	23	8	20	72
11	4	0	96	24	8	30	62
12	4	10	86	25	8	40	52
13	4	20	76				

compacted specimens were 50 mm in diameter and 100 mm in height. All of the samples were wax coated and cured in a temperature controlled chamber at an average temperature of 44 °C for 7 and 14 days. The unconfined compressive strengths of cured samples were determined in a strain controlled unconfined compression testing machine at strain rate of 1.2 mm/min. The average UCS values (three identical specimens) of different mixes of fly ash–GBFS–cement after 7 and 14 days curing were determined and are presented in Tables 5 and 6, respectively.

2.2.3. California bearing ratio (CBR) test

The California bearing ratio test is a method for evaluating the stability of soil subgrade and other flexible pavement materials. CBR is defined as the ratio of the load sustained by the specimen at 2.5 or 5.0 mm penetration to the load sustained by standard road aggregates at the corresponding penetration level. The standard load values are 13.44 and 20.16 kN, respectively, at 2.5 and 5.0 mm penetration. The CBR value of different mixes of fly ash, slag and cement were determined as per IS: 2720 (Part-16), 1979. CBR specimens were prepared by adding water corresponding to their OMC and were compacted to their corresponding MDD using static compaction method. The samples were cured in hot water at an average temperature of 44 °C for 7 days and then tested in a CBR testing machine. For a particular mixture, three identical specimens were prepared and tested. The average CBR values (of three specimens) for different mixes are given in Table 7.

3. Discussion

3.1. Compaction characteristics

The variation of MDD and OMC with cement content is shown in Figs. 2 and 3, respectively. Addition of cement to fly ash–slag mixture results in an increase of MDD and decrease of OMC. The specific gravity of cement particles is higher than that of fly ash and slag. Replacement of a certain percentage of fly ash or slag by cement will increase its mass density. In addition to this, cement particles are comparatively finer than the fly ash and GBFS particles. These finer particles occupy the void space in the compacted mixture, thus reducing the OMC and increasing the MDD of the mixture. The variation of MDD and OMC with slag content is shown in Figs. 4 and 5, respectively. These graphs indicate that the MDD increases and

Table 5
Unconfined compressive strength of 7 days cured specimens (kN/m^2)

Slag (%)	Cement (%)			
	2	4	6	8
0	67.14	105.04	272.80	517.80
10	70.39	119.11	378.47	665.02
20	80.79	187.32	396.31	785.39
30	140.63	346.72	546.32	895.45
40	278.23	525.46	648.23	995.32

Table 6
Unconfined compressive strength of 14 days cured specimens (kN/m^2)

Slag (%)	Cement (%)			
	2	4	6	8
0	193.4	358.3	418.85	839.8
10	235.95	308.25	426.3	938.25
20	272.0	469.85	508.15	1037.23
30	282.0	476.35	532.5	1124.43
40	396.0	625.32	679.32	1217.46

Table 7
Average California bearing ratio (CBR) value of stabilized mixes (7 days cured samples)

Slag (%)	Cement (%)				
	0	2	4	6	8
0	2.00	15.38	30.82	45.72	62.45
10	2.18	17.26	33.29	58.65	79.73
20	2.31	21.04	38.73	72.33	84.94
30	2.46	24.78	41.66	78.54	89.96
40	2.98	26.57	49.79	96.51	105.73

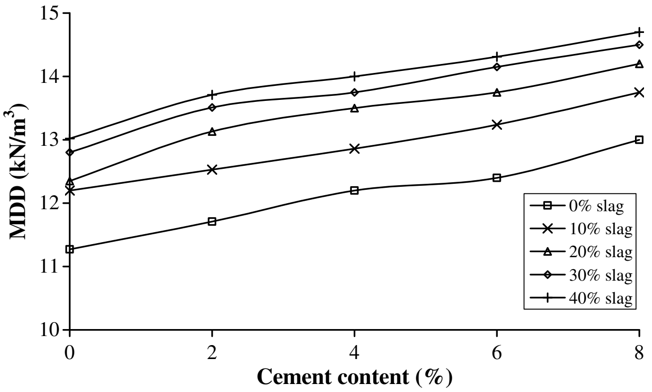

Fig. 2. Variation of maximum dry density (MDD) with cement content.

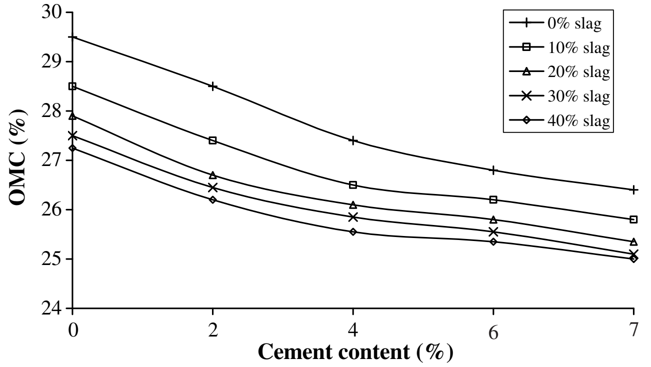

Fig. 3. Variation of optimum moisture content (OMC) with cement content.

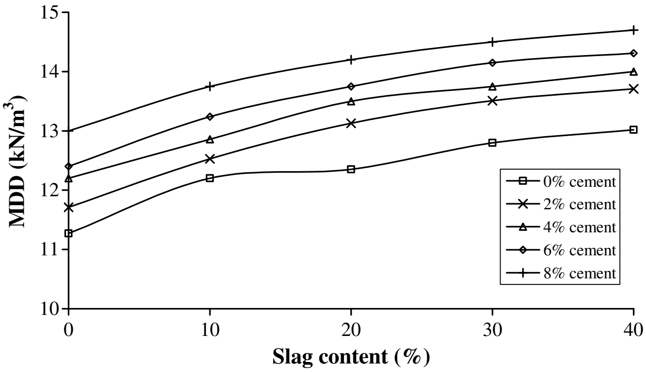

Fig. 4. Variation of maximum dry density (MDD) with slag content.

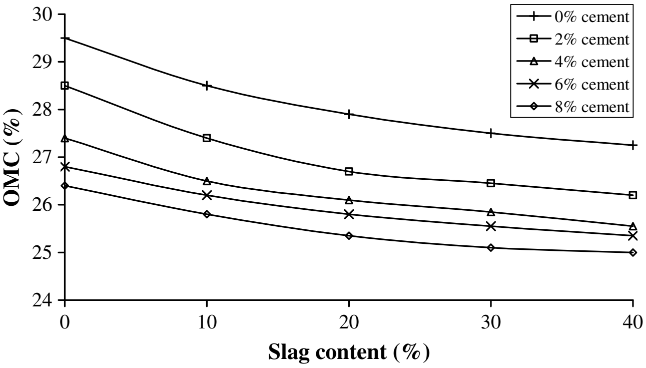

Fig. 5. Variation of optimum moisture content (OMC) with slag content.

the OMC decreases with the addition of slag to fly ash–cement mixture. Addition of GBFS to fly ash–cement mixture results in a well graded mass. Hence, with the same compactive energy, the mixture is compacted to a higher density, resulting in an increase in MDD and decrease of OMC value. Moreover, the specific gravity of slag is slightly more than that of fly ash. Hence replacement of fly ash by the same amount of slag will certainly increase the dry density of the compacted mass. Jones (1958), Shastry and Kumar (1989) have reported that an addition of lime or cement to soil decreases the dry density of the compacted mixture due to flocculation and aggregation of soil particles, resulting in an increase void of the mix. However, in the present case, with mixes of fly ash–slag, no such behavior is observed. It may be concluded that the cement added to the fly ash–slag mixture is totally utilized for hydration of cement reaction rather than the reactions like base-exchange, aggregation and flocculation.

3.2. Unconfined compressive strength

The unconfined compressive strength of fly ash–GBFS–cement mixes, after 7 and 14 days of curing is summarized in Tables 5 and 6, respectively. It is observed that the unconfined compressive strength increases with increase in cement content. During the hydration of cement, C_3S and C_2S present in cement react with water forming complex calcium silicate hydrates (C–S–H). The C–S–H gel thus formed, fills the void space and binds the particles together imparting strength to the mass. With increase in cement content in the mixture, the quantity of gel formation increases, which binds the particles more effectively. There is also an appreciable gain in strength with addition of GBFS at constant cement content. GBFS contains highly reactive siliceous and aluminous materials in a finely divided form known as pozzolana. These pozzolanic materials, in presence of water react with calcium hydroxide liberated during hydration of cement to form compounds (C–S–H gel) possessing cementing properties. In addition to this, GBFS contains free lime which undergoes pozzolanic reaction with silica and alumina resulting in gel formation. This indicates that addition of GBFS to a mixture of fly ash–cement is certainly advantageous in increasing the strength of stabilized mixes. Secondly, addition of GBFS to fly ash makes the mix well graded, thus increasing the compacted density and hence the mechanical strength of the compacted mixture. It is also observed that the strength of compacted mixes increases with curing time.

3.3. California bearing ratio (CBR) value

Table 7 gives the average CBR values of different fly ash–GBFS–cement mixes after 7 days of curing. It is noticed that the CBR value of the specimen increases enormously with addition of cement. At 0% cement, the CBR value of the compacted fly ash is 2%, but it is increased to 62.5% at 8% cement content, which is about 31 times the strength of compacted fly ash alone. Both fly ash and GBFS are granular particles having no cohesion between the particles. The strength offered by the compacted fly ash–GBFS sample is mainly due to the mobilization of frictional strength of the materials. Addition and subsequent hydration of cement forms the insoluble C–S–H gel, which is responsible for binding the fly ash and GBFS particles together and thus adding the cohesive strength of the mass. With increase in cement content in the mixture, the

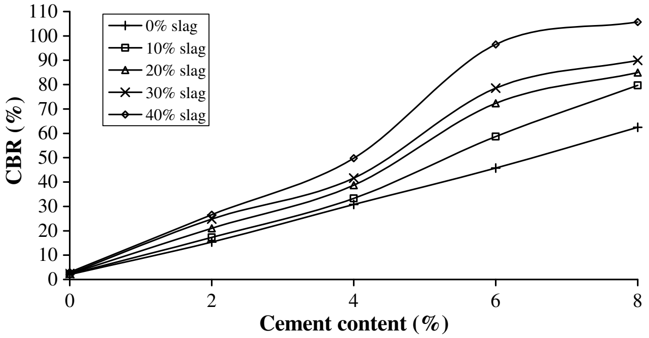

Fig. 6. Variation of California bearing ratio (CBR) value with cement content.

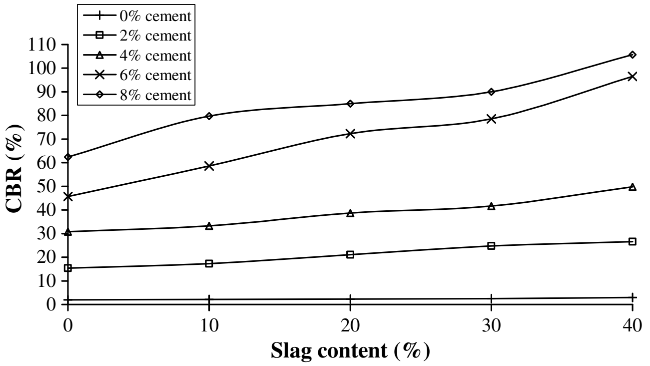

Fig. 7. Variation of California bearing ratio (CBR) with slag content.

Table 8
Ratio of CBR and UCS values (at 7 days of curing)

Slag (%)	Cement (%)			
	2	4	6	8
0	0.229	0.293	0.167	0.120
10	0.245	0.279	0.155	0.120
20	0.260	0.206	0.182	0.110
30	0.176	0.120	0.143	0.100
40	0.095	0.094	0.149	0.106

quantity of gel formation increases, which binds the particles more effectively resulting in higher CBR value. A linear relationship is observed between the CBR value and the cement content (Fig. 6).

Similarly with a fixed amount of cement, an increase of slag content increases the CBR value (Fig. 7). For example, at 2% cement and 0% GBFS, the CBR value is 15.4% which increased to 26.6% when the GBFS content is increased to 40%. This increase of CBR value can be attributed to the increase in mechanical strength of the fly ash–GBFS–cement mixture over the fly ash–cement mix. GBFS contains free calcium oxide in addition to reactive silica and alumina. The reactive silica and alumina undergoes pozzolanic reaction with calcium hydroxide liberated during hydration of cement or free calcium oxide present in the GBFS sample in the presence of water. This results in formation of insoluble C–S–H gel, which is responsible for increase in CBR value of the specimen. Hence, addition of GBFS to fly ash–cement mixes is advantageous in gaining a higher CBR value.

In order to find out the relationship between the CBR and UCS values of cement stabilized fly ash–GBFS mixes, the ratio of CBR to UCS value are calculated. These are shown in Table 8. However, no definite relationship can be established between these parameters.

4. Conclusion

Based on the findings of the present investigation, the following conclusions are reached:

- Fly ash is more or less a well-graded material having specific gravity lower than the natural inorganic soil. The low specific gravity is due to the presence of cenospheres.
- An increase of either cement or GBFS content in the mixture results an increase of MDD and decrease of OMC of the compacted mixture. The MDD of the cement stabilized fly ash–GBFS mixture is comparably lower than the similarly graded natural inorganic soil. This is advantageous in constructing lightweight embankments over soft, compressible soils.
- Almost a linear relationship is found between the unconfined compressive strength of the mixture and the cement content. An increase of GBFS quantity in fly ash at a given percentage of cement improves its compressive strength.
- The compressive strength of stabilized mixes increases with curing period. The ratio of UCS values at 14 and 7 days of curing is found to be higher for low slag contents, indicating that the addition of slag to the fly ash–cement mixes accelerates the pozzolanic reaction.
- An increase in the percentage of cement in the fly ash–GBFS mix increases enormously the CBR value. Also an increase of the amount of GBFS in the fly ash sample with fixed cement content improves the CBR value of the stabilized mix.
- No definite relationship is observed between the UCS and CBR values of stabilized fly ash–GBFS mixes.
- A CBR value of 105% is obtained for a mix of fly ash:GBFS:cement in the proportion of 52:40:8.
- An appropriate mix with required CBR value can be prepared for various layers of flexible pavement, enabling the use of these waste materials in highway construction.

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