Self-Consolidating Paving Grade Geopolymer Concrete

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Abstract: The cement concrete used in the construction of rigid pavement is usually stiff mix with a low slump. The concrete of this type requires a high degree of compaction which is achieved employing needle vibration or roller compaction technique in the field. The vibration technique may sometime leave vibratory trails, and roller compaction concrete produces over or under consolidated concrete, and both methods are also known to be energy intensive. This issues can be overcome by the adoption of self-consolidating concrete for the construction of rigid pavement. However, the self-consolidating paving technique is an uncommon scenario. In this connection, an attempt was made produce a self-consolidating geo-polymer concrete. This paper presents an investigation carried on the novel geo-polymer concrete which is self-consolidating, sustainable and can be espoused for fixed form paving application. The geo-polymer concrete mix used for the study was prepared from class F fly-ash, GGBS, alkaline solution (NaOH and Na₂SiO₃), coarse aggregate and quarry dust as fine aggregate. The mix was designed to cure at ambient condition and possess a target compressive strength of 40 MPa. The properties of concrete during paste phase and hardened state were investigated and the results of the tests are presented and discussed here. Also reported here are the results of flexural strength test performed on beams sliced out from the micro slabs, which ascertained the self-consolidation of the geo-polymer concrete mix.

1. Introduction

The pavements are structural elements designed to withstand the stress due to wheel loads and temperature. They are multi-layered and can be of types: flexible, cement concrete pavement (CCP) and composite system. In India, the flexible pavement is widely preferred. However, CCP due to its superior performance concerning load carrying capacity, durability, low maintenance and service life, is equally finding its broad applications especially in coastal and rural regions of India. Conventionally, the CCP is made up of cement concrete also known as Pavement Quality Concrete (PQC) layer at the top followed by dry lean concrete (DLC) layer at the middle and subgrade at the bottom [22]. A PQC is composed of cement, coarse aggregate and fine aggregate all mixed with water to produce a low slump homogenous mix [23]. The environmental issue associated with the production of cement, depleting natural coarse and fine aggregate resource has made cement concrete unsustainable. Copious amount of research is going on globally to produce more eco-friendly cement concrete. Although there have been significant efforts made to partially replace the cement with industrial by-products such as fly-ash, blast furnace slag, silica fume etc.in cement concrete, the 100% replacement of cement is achieved recently.
in Geopolymer Cement (GC). GC is an alkali-activated fly-ash based eco-friendly cement in which fly-ash obtains the cementing property by the polymerisation process. A PQC mix with GC and other alternatives to conventional aggregates can become a viable option to produce a sustainable rigid pavement and was the primary motivation of presented study.

The construction of CCP in India is usually carried by the method of Roller Compaction Technique (RCT). However, the CCP construction by Slip Form Paving Technique (SFPT) is also gaining equal importance now-a-days. In RCT the cement concrete is laid over a base course between the edge formwork and consolidated with vibratory rollers to achieve desired compaction and surface finish. Whereas in SFPT the placing of concrete mixture, casting, consolidation and finishing is performed sequentially as one unique process thus facilitating speedy construction. Both the methods of pavement construction demands for the concrete mixture having zero or low slump. The concrete having zero or low slump has low consistency hence requires vibration more than usually during its consolidation to remove the entrapped air. More significantly the problem of excessive or under consolidation is common in RCT. On the other hand, SFPT often leaves vibratory trails affecting concrete’s freeze-thaw durability. Furthermore, both the methods of pavement construction are known to be energy intensive also. These problems can also be overcome with the adoption of paving grade geopolymer cement concrete which is self-consolidating.

1.1. Self-consolidating paving grade cement concrete (SPGCC)

The SPGCC requires a matrix in the plastic state which has low slump with little flow-ability yet, possessing the ability to consolidate on its own. The self-consolidating concrete can be developed for slip form and fixed form paving applications. The proper balance between fine particles and plasticiser needs to be established to produce a better workable and sufficient green strength (shape holding ability) SPPGC [1]. The fine particles such as nano clay types: Actigel, Metamax and Concresol can successfully improve the flow and shape stability properties [1, 17, 18]. Whereas plasticisers such as viscosity modifying agent and Magnesium oxide may aid in the development of sufficient the green strength in concrete [17]. The addition of Na$_2$SO$_4$ and CaCl$_2$ reduces the slump of the mix although it increases the early strength [17]. The water-retaining polymer can slow down of setting time and hardening of the slump. The lignosulphonic or hydroxylated carboxylic acids based retarders delays the setting time, and when used in excess may also accelerate the setting time of cement paste [17]. In addition to the clays and admixtures, fibers such as Polypropylene fibers can aid in improving the green strength and hardened state strength properties of SPGCC [2]. The SPGCC is found to exhibit desirable mechanical strength properties [16]. However, it has poor shrinkage and elasticity properties in the hardened state [3].

1.2. Geopolymer concrete

The term Geopolymer refers to an inorganic polymer consisting of a chain-like structure formed by essential components such as Al and Si ions [19]. The production of geopolymer involves alkali activation of source material which are rich in aluminosilicates. The alkali solutions can be NaOH or KOH and a soluble silicate such as Na$_2$SiO$_3$ or K$_2$SiO$_3$. The chemical reaction between the source material and alkali activator is typically a polymerisation process. The mechanism is therefore called as geopolymerisation. The synthesis process results in formation of three dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds [19, 20, 21]. The product is amorphous in microstructure and possess binding property hence can be used as a cementing material for construction works. Recently emphasis is given to understanding its various features and potentials as a sustainable alternative to Portland cement. The factors such as the source materials, activators, curing regime and admixture significantly effects the fresh and hardened properties of geopolymer cement concrete. The commonly used source materials are are clays – kaolin and metakaolin, fly ashes – high and low calcium based, blast furnace slag and combined types such as fly ash and slag, fly ash and clay, slag and clay [4, 5]. Although the clay-based geopolymer concrete can be consistently produced, its flaky particles are known to pose some rheological difficulties [6]. On the other hand, the fly ash and slag based
geopolymer concrete have advantages of being durable and stronger than clay-based geopolymers [7]. The \( \text{SiO}_2/\text{Al}_2\text{O}_3 \) ratio, \( \text{R}_2\text{O}/\text{Al}_2\text{O}_3 \) ratio, \( \text{SiO}_2/\text{R}_2\text{O} \) (\( \text{R} = \text{Na}^+ \) or \( \text{K}^+ \)) and liquid-solid ratio significantly affects the hardened properties of geopolymer concrete [8]. The increase in alkali content or decrease in silicate content in \( \text{SiO}_2/\text{R}_2\text{O} \) ratio increase the compressive strength of the geopolymer concrete. The higher activator dosage reduces the pores and increases the strength. The \( \text{SiO}_2/\text{Al}_2\text{O}_3 \) ratio between 3.0-3.8 and \( \text{Na}_2\text{O}/\text{Al}_2\text{O}_3 \) ratio of 1 is considered to produce geopolymer concrete with optimum strength. The admixtures such as Sucrose retards the setting time and citric acid accelerate the setting time. Whereas, the polycarboxylate based superplasticizer improves the workability of fly ash-slag geopolymer concrete significantly compared to naphthalene based superplasticizer [9]. It is possible to produce geopolymer concrete having compressive strength up to 50MPa at the ambient curing temperature [20]. The geopolymer concrete can also be tailored to obtain self-compacting capability using viscosity modifying admixtures, varying water to binder ratio and powder to activator ratio [10, 11, 12].

1.3. Geopolymer Concrete Pavement
Worldwide, geopolymer concrete is developed to meet the most of the requirements of structural applications. Probably, the construction of turning node, apron and taxiway pavements of Brisbane West Wellcamp Airport [15] signifies one of the large-scale cast-in-situ application of paving grade geopolymer concrete. However, a considerable amount of research is going on to recognise the suitability of geopolymer concrete as paving grade concrete. Few studies [13, 14] reported elsewhere indicates that the geopolymer concrete can become an alternative to conventional Portland cement concrete for pavement application.

2. Experimental Procedure
The Self-consolidating Paving Grade Geopolymer Concrete (SGC) mix was formulated using F-class fly-ash, Ground Granulated Blast Furnace Slag (GGBS), Alkaline activators: NaOH in pellets and solution form (Molarity: - 10 and 12), \( \text{Na}_2\text{SiO}_3 \) (A-53 grade), Coarse aggregate -20mm down, Fine aggregate: River sand and Quarry dust, Retarders: Conplast SP500 and sugar solution, and water; curing regime: ambient cured. All the materials mentioned here were tested for their compliance with specifications [24, 25, 26]. Ten mixes were prepared by varying the proportions of ingredients. The details of the mixes are summerised in Table 1.

| Ingredients                          | M1   | M2   | M3   | M4   | M5   | M6   | M7   | M8   | M9   | M10  |
|--------------------------------------|------|------|------|------|------|------|------|------|------|------|
| Fly Ash (kg/m³)                      | 338  | 275  | 275  | 237  | 330  | 330  | 330  | 330  | 330  | 330  |
| GGBS (kg/m³)                         | 146.3| 275  | 275  | 158  | 220  | 220  | 220  | 220  | 220  | 220  |
| NaOH soln. (kg/m³)                   | 19.25| 5    | 19.25| 45.15| 45.15| 45.15| 45.15| 45.15| 45.15| 45.15|
| \( \text{Na}_2\text{SiO}_3 \) soln. (kg/m³) | 75   | 75   | 75   | 112.88| 112.88| 112.88| 112.88| 112.88| 112.88| 112.88|
| SP (kg/m³)                           | -    | -    | -    | -    | -    | -    | -    | -    | -    | -    |
| Table Sugar (1.5% of binder content) (kg/m³) | -    | -    | -    | -    | -    | -    | -    | 8.25 | 8.25 | 8.25 |
| F.A (quarry dust) (kg/m³)            | 735  | 555  | 555  | 735  | -    | 735  | 735  | 735  | 735  | 735  |
| F.A (river sand) (kg/m³)             | -    | -    | -    | 555  | -    | 735  | -    | -    | -    | -    |
| C.A (kg/m³)                          | 870  | 850  | 850  | 1290 | 870  | 870  | 786  | 786  | 786  | 786  |
| Water (kg/m³)                        | 170  | 170  | 159.5| 39.5 | 41.8 | 24.75| 41.8 | 41.8 | 41.8 | 55   |
| \( \text{Na}_2\text{SiO}_3/\text{NaOH} \) | 3.89 | 3.89 | 3.89 | 0.28 | 2.5  | 2.5  | 2.5  | 2.5  | 2.5  | 2.5  |
| Water to GPS ratio                   | 0.39 | 0.35 | 0.33 | 0.1  | 0.213| 0.19 | 0.213| 0.213| 0.213| 0.23 |
| Alkaline to Binder ratio             | 0.20 | 0.17 | 0.17 | 0.4  | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 |
3. Results and discussion of fresh state properties
The slump cone test, spread test, compaction factor test and green strength test were performed to investigate the fresh state properties. The slump value: 152.4mm (6”) to 203.2mm (8”), spread value: 279.4mm (11”) to 330.2mm (13”), compaction factor value :> 95% and green strength value: 1.3 to 2.5kPa were considered as desired values to be possessed by a SGC for slip-form paving application. These tests were conducted as per the specifications IS: 1199 – 1959 [28]. The results of afore mentioned tests are presented in the table 2. The mixes M1 and M2 showed rapid hardening effect in the concrete mixer itself. Although M3 and M4 produced desired results, both the mixes were also set quickly. M5 had slump value slightly more than the required. Whereas M6 and M7 failed to possess green strength with slump value beyond the desired level. While M8 exhibited collapsed slump, inconclusive spread and no green strength. Test results of M9 also indicated almost nil green strength with slump and spread values exceeding anticipated values. In view of scarce availability of natural sand and also better performance in terms of slump, spread and relative slower setting time offered by mix M10, disregarding its poor green strength, was finalized in order to investigate its hardened properties as SGC. The results of compaction factor test inferred that all the mixes achieved a compaction of above 98%. This study was conducted with an intention to develop a low slump self-consolidating slip-form paving grade geopolymer concrete. Since, all the mixes failed to achieve green strength, which is an important criterion to ascertain the slip-forming pavement grade, the investigation proceeded with exploring the possibility of using the developed concrete for fixed forming paving applications. For this a slab of 100mm*100mm*500mm was casted and beams sliced out from the slab were tested for flexural strength after desired curing period.

Table 2. Fresh state properties of SGC.

| Mixes designation | Slump (mm) | Spread (mm) | Green strength (kPa) |
|-------------------|------------|-------------|---------------------|
| M1                | 190        | 279         | 1.896               |
| M2                | 203        | 304         | 3.080               |
| M3                | 215        | 393         | 1.300               |
| M4                | 228        | 419         | Failed              |
| M5                | 228        | 406         | Failed              |
| M6                | Collapsed  | -           | Failed              |
| M7                | 254        | 431         | Failed              |
| M8                | 203        | 330         | Failed              |

4. Results and discussion on hardened state properties of M10 mix
The results of compressive strength test, flexural strength test, split tensile strength test and Modulus of Elasticity of mix M10 are presented in the table3. These tests were performed as per IS: 516 – 1959 [27]. The average compressive strength of M10 mix after 28 days of ambient curing was found to be 56.47MPa which is 40% more than the target compressive strength. Here the target compressive strength adopted was 40MPa which is said to be the min. stipulated strength a paving grade concrete should possess in India [22, 23]. The compressive strength gradually increased to 71.78MPa upon 56 day of ambient curing. This increase in compressive strength is because of pozzolanic action of fly-ash in the presence of GGBS and alkaline activators. The table also indicates gradual increase in flexural strength from 7 days to 56 days of ambient curing with 40% increase. The percentage increase in split tensile strength was found to be 25% for 28 days to 56 days of curing. Further, the flexural strength test results of the sliced out beams from the slab indicated that the developed concrete mix possessed sufficient flexural strength and desired level of self-consolidation.
Table 3. Hardened properties of M10 mix.

| Curing Period in Days | Compressive strength (MPa) | Flexural Strength (MPa) | Split Tensile Strength (MPa) | Modulus of Elasticity (MPa) | Flexural strength of beams sliced form slab |
|-----------------------|----------------------------|-------------------------|-----------------------------|---------------------------|------------------------------------------|
| 7                     | 45.22                      | 3.85                    | -                           | -                         | 4.05                                     |
| 28                    | 56.41                      | 4.63                    | 3.96                        | 37471.44                  | 4.95                                     |
| 56                    | 71.78                      | 5.42                    | 4.96                        | 38197.20                  | 5.22                                     |

5. Conclusion
The proposed SGC mixes failed to exhibited sufficient green strength which is vital for slip-form paving applications. The reasons for loss of green strength in SGC mixes can be attributed to low yield stress and low viscosity. Studies have indicated that the incorporation of nano clay and fibers can improve the shape holding ability. Thus, the current investigation can be extended further by adding nano clay and/or fiber into SGC to gain green strength and make it suitable for slip-form applications. The developed SGC mixes demonstrated decent hardened properties as a result it can be used for fixed for paving grade applications. Also, the SGC acquired an average compressive strength of 40MPa and more in 7days. This is of greater significance as it may facilitate the opening of road to traffic ahead of time.

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