Application of Cement Kiln Dust as Activator of Ground Granulated Blast Slag for Developing A Novel Cold Mix Asphalt

Ruqayah Al-khafaji¹, Anmar Dulaimi ², Monower Sadique ³, Ayat Aljsane⁴

¹ Assistant lecturer, Al-Mustaqbal University College, Building And Construction Technology Engineering Department, Al-Najaf street, Hillah, Iraq, ruqayah.hayder@mustaqbal-college.edu.iq
² Lecturer, Department of Civil Engineering, College of Engineering, University of Warith Al-Anbiyaa, Karbala, Iraq; Ministry of Education, Karbala, Iraq; University of Kerbala, Karbala, Iraq, a.f.dulaimi@uowa.edu.iq; a.f.dulaimi@karbala.edu.iq
³ Reader in Civil Engineering, Liverpool John Moores University, Peter Jost centre, Byrom Street, Liverpool, L3 3AF, UK, M.M.Sadique@ljmu.ac.uk
⁴ Assistant lecturer, Department of Economics, Hillah University College, Al- Najaf Street, Hillah, ayataljsany933@gmail.com

Abstract. The use of Cold bitumen emulsion mixtures (CBEMs) is associated with many issues which are the high air content, low strength at early ages and requiring long curing time as well as its high water sensitivity. This research aims to develop a new cold mix asphalt to be used as a binder course by utilising waste materials. So, ground granulated blast slag (GGBS) and cement kiln dust (CKD) were used as fillers in a polymer modified emulsion. GGBS was incorporated to replace the traditional fillers (limestone dust), meanwhile, CKD was used as an activator. Indirect tensile stiffness modulus (ITSM) was used to examine the mechanical characteristics and water sensitivity was measured via the stiffness modulus ratio (SMR). Meanwhile, the microstructure of the specimens was examined using scanning electron microscopy (SEM). The results indicated significant improvement in the mechanical properties as well as the water sensitivity with the incorporation of GGBS and CKD. These enhancements were confirmed by SEM which attributed that to the formation of hydration products at the early ages of specimens.

Keywords: Cold bitumen emulsion mixtures, cement kiln dust, ground granulated blast slag, SEM.

1. Introduction
The preparation of cold bituminous emulsion mixtures (CBEMs) requires incorporating cold aggregates with filler, asphalt emulsion and water at room temperature [1]. UK and France are the first countries trying this technology starting in 1970. These countries have gained outstanding knowledge in the performance of the CBEMs. On the other hand, the relatively cold weather in the UK which is not favourable for curing the emulsion mixture made the use of CBEMs not embraced [2]. However, the
use of CBEMs in the UK was allowed after publishing the specification for reinstatement of opening in Highways in 1992 by the Highway authorities. The specification allowed replacing hot mix asphalt with Cold Lay Surfacing Materials in reinstating low traffic roads and footways. The utilisation of CBEMs becomes favourable due to the significant issues of hot mix asphalt (HMA) like energy consumption, CO$_2$ emission and global warming [3, 4].

Nowadays, the attention of the industry moves toward sustainable construction to save energy and reduce CO$_2$ emissions [5-10]. CBEM is one of the materials adopted due to its low energy consumption. Accordingly, removing the need for heating a large volume of aggregates is associated with many economic and environmental outcomes [11]. However, those mixtures have properties significantly lower than that of hot mix asphalt due to the high air void contains, water sensitivity and long curing time ranging from (2-24) months [12-14]. Serfass et al. [15] considered CBEMs as evolutionary materials as they gain strength gradually as the materials dry. While the hot mix asphalt can achieve the whole strength rapidly as the materials cool. Jenkins [16] indicated that CBEMs obtain strength when the moisture is excluded.

To enhance the characteristics of CBEMs, cement has been utilised as filler in order to strengthen the structure of the mixture by creating a secondary binder and absorbing the water in the voids resulting in early strength. Ordinary Portland Cement (OPC) was utilized in the CBEMs by various researchers [17, 18]. Those researchers proved that cement plays a major role in enhancing the early stiffness, increase durability and improve the rutting resistance of the mixtures. But cement is very expensive and its production leads to CO$_2$ emission. Hence, waste and by-product materials like fly ash, GGBS and CKD have the potential to be utilized in CBEMs as a substitute to OPC. The utilisation of these materials is very promising due to its environmental sustainability and economic merits.

Ellis et al. [19] indicated that the use of ground granulated blast slag (GGBS) as filler in the bitumen mixtures improved its mechanical performance compared to the untreated mixtures, but the development of strength is very low, hence other materials like lime and cement is required to enhance the strength development. Another research carried out by Al Nageim et al. [20] developed new CBEMs with durability and mechanical characteristics compared to the traditional HMA by using fly ash. In spite of the current research on developing CBEMs, there is no research presented on manufacturing CBEMs incorporating GGBS and cement kiln dust (CKD) and polymer-modified emulsion to be used as a binder course. The mechanical characteristics of the new CBEMs were examined using the indirect tensile stiffness modulus (ITSM), while water sensitivity was measured by the mean of stiffness modulus ratio and scanning electronic microscopy (SEM) analysis was utilised to indicate the microstructure.

2. Materials

2.1 Aggregates

Crushed granite with gradation given in Table 1 and physical properties are given in Table 2, were used in both CBEMs and control HMAs. This aggregate was collected from Carnsew quarry at Mabe in Penryn, UK. The aggregate was dried, rifled, bagged and sieving analysis was conducted following BS EN 933-1 [21]. In the research, as gradation for the aggregate, a 20 mm dense binder course was utilized which was chosen according to BS EN 13108-1 [22] with the gradation curve given in Figure 1. Dense bitumen macadam mixture was selected as it was the most commonly utilised mixtures as a base and binder course in paving roads in the UK. Add to that the continuous grade gives favourable interlocking between aggregates which results in these materials possessing outstanding load-spreading properties and significant resistance to persistent deformation [23].
Table 1. Grading of AC 20mm aggregate following BS EN 13108 [22].

| sieve size mm | % by mass pass | % by mass pass mid |
|---------------|----------------|--------------------|
| 20            | 99-100         | 100                |
| 10            | 61-63          | 62                 |
| 6.3           | 47             | 47                 |
| 2             | 27-33          | 30                 |
| 0.250         | 11-15          | 13                 |
| 0.063         | 6              | 6                  |

Figure 1. Grading of AC 20 mm aggregates following BS EN 13108.

Table 2. The physical characteristics of the crushed granite aggregate

| Selected Materials | properties          | Values          |
|--------------------|---------------------|-----------------|
| Coarse aggregate   | Bulk density        | 2.62 Mg/ m³    |
|                     | Apparent density    | 2.67 Mg/ m³    |
|                     | Water absorption    | 0.8%           |
| Fine aggregate     | Bulk density        | 2.54 Mg/ m³    |
|                     | Apparent density    | 2.65 Mg/ m³    |
|                     | Water absorption    | 1.7%           |
| Limestone filler   | Particle density    | 2.57 Mg/ m³    |

2.2 Bitumen emulsion and asphalt

In the research, cationic bituminous emulsion with a slow setting incorporating polymer (C 50 BP5) with 50/70 base bitumen was utilized to fabricate all the cold bituminous emulsion mixtures since it is capable of coating aggregates in a proper manner and give adequate adhesion between aggregate particles [13, 24]. The emulsion type is called Sprayco CP 50 and was provided by Jobling Purser. For preparing hot mix specimens for comparison purposes, soft bitumen with penetration grade (100/150) was used. This bitumen was supplied by NYNAS.
2.3 Selected Fillers

In this study, four kinds of fillers were utilized. These are the conventional mineral filler (limestone dust (LD)), GGBS provided by Hanson Cement Group which was used to replace the mineral filler (LD), CKD supplied by CEMEX to work as an activator for GGBS and OPC to manufacture the control CBEM mixtures to be used for comparison.

The chemical composition of GGBS which is a by-product of iron manufacture consists of lime, alumina, silica, magnesium and sodium as given in Table 3. On the other hand, CKD is a fine powdery by-product of cement manufacture. CKD utilized in this research was collected using a dry process kiln and gathered by a baghouse. The main oxides of CKD are lime, silica, magnesium and sodium as given in Table 3. CKD was reported to consist of a high amount of alkalis, free lime, and sulfates thus it works as an excellent activator for GGBS [25].

The chemical analysis of the fillers was conducted utilizing Shimadzu EDX 720, energy dispersive X-ray fluorescence spectrometer while the pH was measured using a pH meter in which 3% of the filler was mixed with the water then the solution was tested at ambient temperature (20 °C).

| Filler | CaO | SiO₂ | Al₂O₃ | MgO | Fe₂O₃ | SO₃ | K₂O | TiO₂ | pH  |
|--------|-----|------|-------|-----|-------|-----|-----|------|-----|
| LD     | 5.58| 53.60| 9.22  | 4.98| 7.37  | 0.0 | 3.12| 0.81 | 6.05|
| GGBS   | 40.10| 37.80| 5.85  | 4.32| 0.01  | 0.0 | 0.61| 0.68 | 8.4 |
| CKD    | 51.3 | 12.7 | 3.43  | 0.52| 2.6   | 4.1 | 5.6 | 0.0  | 12.80|
| OPC    | 62.58| 25.06| 2.26  | 1.59| 1.82  | 0.0 | 0.75| 0.40 | 12.1|

3. Sample preparation

In spite of the fact that there is no acceptable procedure for designing cold bituminous emulsion samples, authorities like (Asphalt Institute; 1989) and researchers like [3, 26, 27] have established some procedures. This research adopted the method presented by the Asphalt Institute (Marshall Method for Emulsified Asphalt Aggregate Cold Mixture Design (MS-14)) [28] to design the CBEMs samples.

The lowest water content that gives the optimum coating was indicated by examining various pre-mixing water contents. The optimum emulsion content was investigated by indirect tensile stiffness modulus, while the dry density test was utilized to find the optimum water content at compaction. According to the aforementioned tests, the pre-mixing water content was 3.5%, the optimum emulsion percentage was 12.8% and the optimum total liquid percentage at compaction was 12.5%.

The aggregates, filler and pre-mixing water were mixed by Hobart mixer for approximately 1 min. After that, the emulsion was incorporated at the calculated amount and mixed for an additional 1 min. Then, the samples were put in a mould with 150 mm in diameter. Finally, the samples were compacted by applying 50 blows on each face utilizing Marshall Hammer. The compaction was carried out under BS EN 12697-30 [29]. Table 4 shows the mix proportion adopted in this study with the designations.

| Mixtures                               | Designation | LD | GGBS | CKD | OPC |
|----------------------------------------|-------------|----|------|-----|-----|
| Cold mix incorporating limestone dust (control mix) | CL          | 6% | 0%   | 0%  | 0%  |
| Cold mix incorporating 3% limestone and 3% GGBS | CL-G3       | 3% | 3%   | 0%  | 0%  |
| Cold mix incorporating 6% GGBS         | C-G6        | 0% | 6%   | 0%  | 0%  |
| Cold mix incorporating 6% GGBS and 1% CKD | CG-K1       | 0% | 6%   | 1%  | 0%  |
| Cold mix incorporating 6% GGBS and 2% CKD | CG-K2       | 0% | 6%   | 2%  | 0%  |
| Cold mix incorporating OPC (control mix) | C-O         | 0% | 0%   | 0%  | 6%  |
4. Testing programme

4.1 Indirect tensile stiffness modulus test (ITSM)
This test indicates the ability of each pavement layer to transform the load to the lower successive layers. The test is non-destructive and mainly utilized to examine the stiffness modulus of HMA. In bituminous mixtures, tensile stiffness is normally investigated due to the high sensitivity of bituminous mixtures to tensile stress rather than compressive stress. Add to that, ITSM is widely examined because of its high practicality in comparison with other tensile tests like the direct tensile test. This test results in eccentric stress when loading the samples during the examination.

The test was conducted per BS EN 12697-26 [30] at an ambient temperature of 20 °C. The test specimens were examined with the use of HYD 25 apparatus shown in Figure 2 under conditions given in Table 5.

The curing protocol adhered to that adopted by the Asphalt institute which was set in two phases. The first one involved maintaining the samples in the mould for a day at 20 °C. In the second phase, the samples were extruded out of the mould and placed in the ventilated oven for another day at temperatures of 40 °C. Such protocol simulates 7 to 14 days in the field [16]. The specimens were then preserved in the lab at 20°C to be tested at various ages (2, 7, 14 and 28 days).

The limestone dust was substituted by GGBS at various percentages (0, 3 and 6 % by total weight of aggregates). After that, CKD was incorporated by 1% and 2% to the bituminous mixtures with 6% GGBS. It was reported that a substantial development was achieved in the properties of CBEMs by adding an extra silica fume filler [31]. So, this stage includes the addition of extra CKD to the GGBS to facilitate additional activation of the hydration process. The results were compared with the control mixes which were CBEMs incorporating limestone dust, CBEMs with OPC as well as AC 20 hot mix binder course. The hot mix utilized in this study was a hot dense binder course 100/150 having aggregates similar in gradation and type to that used in the bituminous mixtures and 4.6% optimum binder as given in the BS EN 13108-1 [22]. The hot mix asphalt samples were fabricated at a temperature equal to (150-160 °C).

| Item               | Range            | Used  |
|--------------------|------------------|-------|
| Rise time          | 124+-4 ms        | 124   |
| Loading time       | 3-300            | 3     |
| Temperature °C     | 20+-0.5          | 20    |
| Sample diameter    | 80, 100, 120, 150, 200 | 150   |
| Sample thickness   | 30-75 mm         |       |
| Number of pluses   | 5                | 5     |
| Compaction         | Marshall 50x2    |       |
| Poisson's ratio    | 0.35 for a temperature of 20 °C | 0.35  |
| Temperature condition | 4hr before testing |     |
4.2 Water sensitivity test
The bituminous mixtures are considered durable when it has the ability to resist the weather because it leads to the degradation of bituminous mixtures. The degradation of aggregates in asphalt is mainly attributed to the presence of water as it causes moisture damage that undermines the stiffness and causes stripping. Hence, it is necessary to investigate the durability of the CBEMs in terms of water sensitivity in order to satisfy the requirement of mechanical characteristics.

Water sensitivity was conducted by examining the stiffness modulus ratio (SMR) following BS EN 12697-12 [32]. SMR is indicated as the retained stiffness which is the ratio of the stiffness of the samples after subjecting to the conditions over the stiffness of samples before subjecting to the conditions. Two sets of specimens were fabricated with three samples for each one of them. The first set of samples was tested dry at room temperature of 20 °C. The sample was extruded from the mould which kept in for 24 hours and stored in the lab for 7 days before testing. The other set was preserved in the mould for a day after fabrication then kept at 20 °C for 4 days. After that, the samples kept in the water then vacuumed for half an hour followed by submerging for another half an hour. Subsequently, the samples were placed in the water at a temperature of 40 °C for 3 days. The two sets of samples were examined by ITSM at ambient temperature. The conditions applied during the test are given in Table 6.

Table 6. conditions for water sensitivity testing

| item                  | Value            |
|-----------------------|------------------|
| Rise time             | 124              |
| Loading time          | 3                |
| Temperature, °C       | 20               |
| Specimen diameter     | 150              |
| Specimen thickness    | 30-75 mm         |
| Numbers of plus       | 5                |
| compaction            | Marshall 50 x 2  |
| Poisson's ratio       | 0.35             |
| Temperature condition | 4 hr before testing |

5. Results and discussion

5.1 Indirect tensile stiffness modulus
In this study, the replacement of the conventional mineral filler with the new materials was in two stages. The first stage involved substituting limestone dust with GGBS at the rate of 0%, 3% and 6% to
investigate its influence on the behaviour of bituminous mixtures. ITSM test was carried out following [33] after ages of (2, 7, 14 and 28 days). The results showed that subsisting limestone dust by GGBS resulted in a gradual increase in ITSM in all ages (see Figure 3). Besides that, it was found that the increase in the percentage of substitution led to further enhancement in ITSM performance. Nevertheless, the strength percentage of C-G6 was relatively low compared with C-O in all the curing times (see Figure 4). Also, the results showed in Figure 3 indicated that the ITSM performance of C-G6 was significantly lower than that of the hot mix (HMA (100/150)).

The enhancement in the ITSM of CBEMs incorporating GGBS can be attributed to the high lime content of GGBS which is around 40% of the total weight (see Table 5). Al-Busaltan et al. [34] indicated that lime has a significant contribution to hydration as it produces hydration products. Nevertheless, the secondary binder which contributes to the stiffness of CBEMs was created in inadequate amount. This is attributed to the low pH of GGBS which is 8.5 (see Table 5). This pH was not sufficiently high to increase the hydration rate and coalescence. Therefore, Dulaimi et al. [35] indicated that GGBS needs
an activator to accelerate its hydration as alone it shows no considerable improvement in ITSM performance.

The second phase was achieved by incorporating CKD which works as an alkali-sulphate activator in (1% and 2% by dry weight of aggregates) to the CM-GGBS 6. Figure 5 and 6 shows the significant enhancement in ITSM performance during early ages and later ones when CKD added to CM-GGBS 6 compared with CM-OPC and 100/150 HMA. It also indicates that an increase in the percentage of addition is associated with further improvement.

GGBS was activated by CKD due to its high alkalinity which mainly comes from arcanite (K₂SO₄) that plays a significant role in providing the required environment to break the glassy phase of GGBS and initiate the pozzolanic reaction. Add to that the sulphate activation of CKD which is attributed to the presence of sulphate ions in the form of alkali sulphate (K₂SO₄). Moreover, free lime available within CKD causes a further increase in strength by accelerating the hydration rate and as a result increase the hydration products [25].

![Figure 5. The enhancement in ITSM after activating GGBS by CKD](image1)

![Figure 6. Strength percentage of OPC.](image2)
5.2 Water sensitivity
Water sensitivity of the CBEMs was conducted in compliance with BS EN 12697-12: 2008 [36] to investigate their durability. Water sensitivity was examined using the stiffness modulus ratio (SMR). The results given in Figure 7 showed that subsisting limestone dust by GGBS increases SMR by 82% which is considerably higher than the SMR of CL. Nevertheless, the SMR of C-G6 was lower than the SMR of C-O and HMA. The performance of CG-K1 enhanced considerably compared with that of CL. The SMR of CG-K1 was relatively similar to the SMR of HMA (100/150). Nevertheless, it was lower than that of C-O. Additionally, substantial enhancement occurred in the water sensitivity of CG-K2 and it was higher than 100%. SMR higher than 100% was the optimum. The SMR of CG-K2 was the highest value gained in the research overcoming the SMR of CL, HMA (100/150), CG-K1 and C-O. The improvement was attributed to further hydration that occurred when the modified specimens submerged in the water. In addition to the further activation that took place because the samples kept in water under relatively high temperature (40 °C). Moreover, the SMR of CG-K2 was higher than that of CG-K1 due to the further activation of GGBS produced by increasing the percentage of CKD which led to creating further hydration products [31].

5.3 Microstructural analysis
In this study, the microstructural analysis was achieved by conducting Scanning electronic microscopy (SEM). It is the technique utilized to investigate the changes that occurred in the microstructure and the newly-formed cementitious product of the specimens. SEM produced magnified images with high resolution to the surface of the specimens on the microscopic level. In this study, the morphology of the paste consisted of 6% GGBS and 2% CKD was observed at 7 and 28 days. The two fillers were mixed with water to produce the required paste. According to the standard procedure to carry out the SEM analysis, a small fragment of the paste after the due age were taken and coated with the gold then examined using FEI Quanta 200 Scanning Electronic Microscope. Figure 8 a and b shows the microstructure of the (6% GGBS-2% CKD) paste after 7 and 28 days respectively. It is noticed that at 7 days, the morphology of the paste consisted of C-S-H in extensive amount and noticeable formation of needle-like ettringite which formed on the surface of the paste. These hydration products created a dense structure of the paste which is the reason for enhancing the mechanical characteristics. At 28 days, the densification and compactness of the paste were increased with the formation of a higher amount of C-S-H. This is due to the alkali activation of GGBS by CKD. According to the 28 days observations, the strength enhancement and the characteristics of GGBS-CKD mixtures are the results of the formation of C-S-H product, while ettringite was manufactured at an early
age. This means that part of the early strength of the GGBS-CKD was developed by ettringite while any further improvement in the strength is caused by the formation of the C-S-H. These observations are consistent with that of Chaunsali et al. [37].

![Figure 8. The SEM of the (6% GGBS+ 2% CKD) paste at a) 7 days b) 28 days.](image)

### 6. Conclusion

The following conclusions are drawn:

- Subsisting limestone by GGBS in the cold bituminous mixtures increased the ITSM and SMR. The enhancement rate increased with an increase in GGBS content. Nevertheless, the results were not compared with those of C-O and HMA.
- Substantial improvement in the ITSM performance occurred when CKD was utilized to activate GGBS in the cold bituminous mixtures. CG-K1 and CG-K2 gave strength 700% and 1000% higher than that of CL respectively after 2 days only. The stiffness modulus of CG-K1 and CG-K2 was comparable with that of C-O in all the curing ages.
- Further enhancement in ITSM and water sensitivity occurred with the increase in the percentage of CKD from 1% to 2%.
- SEM observation indicated that mixing GGBS with CKD led to the formation of dense structure which further improved with time. The paste also consists of a considerable amount of C-S-H which increased at later age and a noticeable amount of ettringite responsible for the early strength enhancement.
- In this research, the optimum CBEM gained was that incorporating 6% GGBS and 2% CKD (CG-K2).

### 7. Recommendations

The authors recommended using different percentages of CKD such as (2%, 4%, 6% and 8%) by dry weight of aggregates. Also, ITSM, SMR, and SEM can be tested at later ages such as (56, 112, 168, 224, and 336 days). Furthermore, other activators can be tried to activate GGBS like NaOH.
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