UNITED KINGDOM QUALITY ASH ASSOCIATION

Technical Datasheet

Fly Ash in Pavement Construction
Laboratory Mixture Design for FABM

General

Fly ash bound mixtures (FABM) are mixtures of fly ash and other constituents that have a water content compatible with compaction by rolling and a performance that relies on the properties of the fly ash.

Fly ash refers to coal fly ash, also called PFA (pulverized fuel ash) in the UK.

Because of the nature of the coals used in electricity generating power stations, UK fly ashes are primarily siliceous fly ashes. They are thus pozzolanas which, in the presence of quick or hydrated lime [CaO or $Ca(OH)_2$], set and harden when in contact with water.

The fly ash for FABM can be dry run-of-station ash or more usually conditioned (wet) ash, which can be fresh or old stockpiled material. The fly ash for FABM should conform to the requirements for siliceous fly ash in BS EN 14227-4.

> Note: BS EN 14227-4 also covers calcareous fly ash, which is cementitious in its own right without any additions other than water; it is not available in the UK.

In FABM, fly ash is the main constituent of the binder, with lime, quick or hydrated, usually the other binder constituent.

Cement can substitute for lime but is not as effective in mobilising the full pozzolanic and thus cementing potential of the fly ash (Table 1).

Table 1: Compressive strength (R_c) in MPa of treated fly ash

Age of 1:1 sealed cylindrical specimens cured @ 20C	*Fly ash with 2.5% CaO*	*Fly ash with 5% CaO*	*Fly ash with 7% CEM 1*	*Fly ash with 9% CEM 1*
7 days	1.5	2	3	5
28 days	4	4	4	8
91 days	5	7.5	6	9

FABM based on lime are slow-setting, slow-hardening, self-healing mixtures. This more protracted rate of hardening gives lime based FABM;

- In the short term, the laying versatility and immediate trafficability of unbound granular materials,
- In the medium term, the ability to self-heal (autogenous healing) should distress occur through say differential settlement,
- In the long term, the strength and stiffness akin to asphalt and cement bound mixtures (CBM).

Although advantageous for construction purposes, the slow rate of setting and hardening for lime based FABM means that for mixture design purposes, useful results would not generally be available until at least 90 days using normal curing temperatures of 20°C.

At higher temperatures however, the strength development is enhanced and the mixture design for lime-based FABM is therefore typically carried out using 40°C curing so that by 28 days (even 7 days), meaningful results for long-term performance can be obtained using the following;

- R or E (ultimate) ≥ R or E (at 28 days employing sealed storage at 40°C)

NOTE: R denotes strength, either compressive or tensile, and E, elastic or stiffness modulus. Ultimate R or E is deemed the strength at 1 year using 20°C sealed curing and is typically used for pavement design purposes. Extensive testing indicates that the ultimate R or E is typically 1.15 x the 28-day value after 40°C sealed curing.

Where more rapid strength gain is required, say in cold weather, the partial or complete replacement of lime with cement can be employed. However FABM based on cement behave more like cement bound mixtures (CBM) with typically setting commencing after 2 hours and, unless the mixture is mechanically stable to support traffic immediately, requiring a non-trafficking period of 7 days. It follows the mixture design as carried out for CBM. Such FABM also have less capacity for autogenous-healing.

The mixture design processes described here cover all the FABM types standardized in BS EN 14227-3:

- FABM 1: 0/31.5 mm graded mixture
- FABM 2: 0/20 mm well-graded mixture with a compacity (air voids) requirement. [0/14 & 0/10 mm mixtures are also available but would be rarely considered, if at all, for application in the UK]
- FABM 3: sand mixture with an immediate bearing index (IBI), in other words an immediate trafficability, requirement
- FABM 4: mixture with a producer-declared grading
- FABM 5: treated fly ash.

BS EN 14227-3 specifies;

- requirements for the constituents of FABM e.g. the quality of the fly ash, the lime and the aggregates
- requirements for FABM e.g. grading and, where applicable, compacity and immediate bearing index (more later)
- Laboratory mechanical performance requirements for FABM e.g. permitted classes of compressive strength (R_c) and tensile strength/modulus of elasticity class (R_tE).

NOTE: Examples of R_c classes are C1.5/2, C3/4, C6/8, C9/12 and C12/16 where C denotes compressive strength and the 1st number the compressive strength of cylinders with a slenderness ratio of 2 and the 2nd number, cylinders with a slenderness ratio of 1 or cubes. Examples of R_tE classes are T1, T2, T3, T4 and T5, which loosely approximate to the aforementioned R_c classes.

Regarding aggregates, the required properties, say for hardness and shape etc, are selected from BS EN 13242 depending on the position of the FABM in the pavement structure - sub-base or base - and the traffic to be carried (more advice later). Regarding laboratory mechanical performance, the required class of R_c or R_tE is also selected according to application (again more advice later) and the pavement thickness design procedure or recommendations.

The mixture design procedures that follows consider each of the mixture types in turn but;

- concentrate on lime-based rather than cement-based FABM although reference to the latter is discussed where appropriate.

Mixture design procedure for FABM 1 & 2

FABM 1 & 2 are base and sub-base mixtures. Both have to comply with a grading envelope formulated to support immediate trafficking. The mixture design procedure for both is identical with the exception that the latter, FABM 2, has also to satisfy a compacity requirement, which will be explained. FABM 1 & 2 are thus considered together here.

1. Aggregate and fly ash selection and initial proportioning

1.1. The material selection, proportions and specified grading envelopes for FABM 1 & 2 are essentially fixed by the need to produce;

   o a well-graded mixture with the required mechanical robustness and interlock for immediate trafficability

   o a mixture with the necessary amount of fly ash and lime to produce the desired long term performance.

1.2. Concerning grading, it is important that the selected aggregate, with the lime and fly ash, produces a 'smooth' overall mixture grading that complies with the specified grading envelopes for FABM 1 & 2, specifically Figures 1 and 3 respectively, in BS EN 14227-3. A mixture that 'bounces' from one side of the envelope to the other is undesirable for mechanical stability and also long-term performance.

NOTE: Figures 1 & 3 relate to the overall mixture grading of FABM 1 & 2 made from conditioned siliceous fly ash. Do not use Figures 2 & 4 since they relate to calcareous fly ash, which is largely unavailable in the UK, although these figures may/would be applicable say to FABM using dry siliceous fly ash, either pre-blended in the factory with lime or added as a separate constituent via a silo at the mixing plant, or siliceous fly ash / cement combinations.

1.3. For either FABM 1 or 2, depending on the grading and cleanliness of the aggregate, the combined conditioned fly ash / lime proportion should vary between 10 and 15% by mass using, typically, a fly ash / lime ratio of 4. The exact amount of fly ash & lime depends on the required mechanical performance requirements, but whatever the case, it will be significant. Since the binder is mainly silt-sized material, the acceptable amount of fines in the aggregate has also to be low if a mixture with good trafficability is to be achieved. An aggregate with 5% or less passing 63 micron is desirable. Planings, for example, have proved ideal. In addition, the less the material passing the 63 micron, the greater the strength of the mixture. Excess fines in the aggregate just dilutes the hydraulic potential of the lime fly ash combination.

1.4. Equally as important as grading for trafficability and long-term performance, is the quality of the constituents. It goes without saying that better performance will result from the use of hard crushed aggregate than weak or rounded aggregate. Thus it is probable that for the same fly ash / lime content, average quality aggregate and fly ash (some fly ashes are more pozzolanic than others) will achieve C5/6 or C6/8 or T2 strength classes whereas good quality materials should achieve say C12/16 or T4 class.

1.5. The quality of the aggregate for FABM 1 & 2 depends on application and trafficking and suggested guidance on the necessary aggregate properties is given in Table 2 for FABM 1 & 2 and the other FABM types.

1.6. Using 10 to 15% binder addition and grading smoothness as the prime requisites, select the necessary amount of fly ash and lime. If this gives a target '10% fly ash and 2.5% lime' addition by dry mass, then '8% fly ash with 2% lime' and '12% fly ash with 3% lime' should also be tested.

Table 2: Suggested aggregate categories from BS EN 13242 and application guidance for FABM and SFA (subject to site trial to illustrate procedures and performance for FABM 3, 4 and 5 and SFA)

FABM type	***Bases***		***Sub-base subject to significant site traffic***		***Other sub-bases, capping & trench reinstatement***	
	Crushed or broken particles category for aggregate	**Los Angeles coefficient category for aggregate**	**Crushed or broken particles category for aggregate (and or with IBI category for mixture where indicated)**	**Los Angeles coefficient category for aggregate**	**Crushed or broken particles category for aggregate (and or with IBI category for mixture where indicated)**	**Los Angeles coefficient category for aggregate**
1 (& 2)	C90/3	LA50	C90/3	LA50	C50/30	LA60
3	Mixture may be applicable – seek advice from UKQAA		IBI 40	Property not applicable for sand mixtures	IBI 25	Property not applicable for sand mixtures
4	Mixture may be applicable – seek advice from UKQAA		C50/30 & IBI 50	LA50	IBI 50	No requirement
5	Mixture may be applicable for low-traffic bases – seek advice from UKQAA		Mixture generally not applicable		Applicable for use but no aggregate requirements since properties are not relevant	
SFA	Mixture may be applicable for low-traffic bases – seek advice from UKQAA		Mixture may be applicable provided IBI and strength are adequate – seek UKQAA advice		Applicable for use but no aggregate requirements since properties are not relevant	

Notes

1. The IBI test is specified in BS EN 13286-47, Unbound and hydraulically bound mixtures – Part 47: Test method for the determination of the California bearing ratio, immediate bearing index and linear swelling.
2. With the crushed or broken particles category, i.e. C90/3, the first number is the minimum percentage of crushed material and the second the maximum percentage of rounded particles.
3. With the Los Angeles category, LA50 is equivalent to a 10% fines value of 50 kN, and LA60 approximately equivalent to a 10% fines value of 30 kN.
4. Note that where any of the requirements are not met, then a curing and non-trafficking period is required until set commences.

2. Assessment of the selected proportions using strength and or stiffness

The scope/scale of testing will depend on application. Table 3 illustrates the ultimate test schedule. Testing should be undertaken at OMC and also at a wetter water content to ascertain the sensitivity of the mixture to the accidental inclusion of excess water.

Table 3: Full assessment at OMC and or other moisture content

Binder	***Curing temperature***	***Age of test of sealed specimens (days)***							
		7	**14**	**14+14***	**28**	**56**	**91**	**182**	**364**
Fly ash with lime	40°C	XXX	Optional	XXX	XXX	-	-	-	-
	20°C	-	-	-	XXX	Optional	XXX	Optional	XXX
Fly ash with cement	20°C	XXX	Optional	XXX	XXX	-	-	-	-

Note 1: X denotes one specimen for Rc, and/or R_t/E, determination using sealed curing at temperature indicated.

Note 2:* denotes 14 days sealed cure followed by 14 days full un-protected immersion in aerated water – see section 4 titled; 'Durability and volume stability'.

Note 3: For most applications, testing beyond 28 days will usually be unnecessary since 40°C curing will provide the ultimate properties for the lime fly ash combination using the relationship in the introduction. Later age testing is normally only required where a supplier is testing a new mixture prior to putting it in the market place.

2.1. For each of the chosen mixture proportions or just say the target mixture, after mixing together pre-wetted aggregates with the conditioned fly ash and lime, and after allowing the mixture to stand for one hour before use, determine the OMC using the vibrating hammer in accordance with BS EN 13286–4.

2.2. In the case of FABM 2, the compacity of the chosen mixture proportions should also be checked at this stage in accordance with Annex A in BS EN 14227-3. This will require knowledge of the maximum modified Proctor dry density, which will be lower than the vibrating hammer value. This is effectively a theoretical density check to ensure the production of a dense mixture with minimal voids. This may illustrate that the suggested proportioning is inadequate and that adjustments need to be made.

2.3. Using the OMC value and also a wetter value, and using pre-wetted aggregates with the conditioned fly ash and lime, and allowing the mixture to stand for one hour before use, make the necessary number of strength specimens for each combination. Typically, these will be 150mm diameter cylinders with a slenderness ratio of one (two for elastic stiffness testing) made in HDPE moulds with a wall thickness of 10mm compacted using the vibrating hammer method in BS EN 13286-51.

2.4. Leaving the specimens in their moulds and sealing the top and bottom faces, cure the specimens for the necessary periods at 40°C (or at 20°C for fly ash / cement binder combination) and then test in accordance with BS EN 14227-41 for R_c, part 42 for R_t, and part 43 for E to enable the selection of or confirmation of the required proportions against the specified strength requirement.

3. Durability and volume stability

3.1. The resulting mixture proportions should be checked for durability (weather related) and volume stability purposes (should sulfates be present in the aggregate for example) against the following criteria;

- Mixture with C3/4 strength class can be considered resistant to frost heave.
- Volume stability and resistance to water can be assumed if un-protected specimens fully immersed in aerated water for 14 days following 14 days sealed curing, maintain at least 80% of the strength, using either R_c or R_t, of sealed non-immersed specimens cured for 28 days at the same temperature (this is also included in Table 3).

Mixture design procedure for FABM 3 & 4

FABM 3 and FABM 4 are primarily sub-base materials. FABM 4 is also ideal for trench reinstatement since it allows the re-use of trench arisings, and for base application where the mixture grading is reasonably well-graded but falls outside the requirements for FABM 1.

- FABM 3 is a sand mixture with an overall 'mixture grading' requirement and an Immediate Bearing Index (IBI) requirement to check trafficability - the IBI test being an immediate CBR test on the mixture without the use of surcharge rings. The test is described in BS EN 13286-47.
- FABM 4 is a mixture with the requirement that the producer declares the grading. FABM 4 is included in the European standard to allow the use of aggregates that are not sands and thus not suitable for FABM 3 and that would also not produce a mixture with a grading required by FABM 1 & 2, but which in other respects are adequate and thus should not be discounted from use. It would also be usual to check FABM 4 for trafficability using the IBI test.

The mixture design procedure for both can therefore be considered similar and are thus considered together here.

1. Aggregate and fly ash selection and initial proportioning

1.1. As with most FABM, the aggregate or sand selection, and overall proportioning, are essentially fixed;

1.1.1. to produce a mixture for immediate trafficability

1.1.2. with the necessary amount of binder (i.e. fly ash and lime) to produce the desired long term performance.

1.2. For either FABM 3 or 4, experience indicates that the combined fly ash / lime proportion usually needs to be between 15 and 25% depending on the grading and cleanliness of the sand/aggregate, the mechanical performance requirements and trafficability. For the lower percentage, the typical fly ash / lime ratio used is 4, but can be 5 even 6 for the higher percentage provided good production methods are envisaged.

1.3. It is proposed here that aggregate quality for FABM 4 be selected on the basis of Table 2 and initial proportioning be based on achieving as smooth a grading as possible using 15 to 25% binder addition and the IBI values in Table 2. If the result of this exercise gives a target '16% fly ash and 4% lime' addition, then say '12% fly ash with 3% lime' and '20% fly ash with 4% lime' should also be considered.

2. Assessment of the selected proportions using strength and or stiffness

2.1. The process is identical to that for FABM 1 & 2, specifically FABM 1, because there are no compacity requirements for FABM 3 & 4.

3. Durability and volume stability

3.1. As FABM 1 & 2.

Mixture design procedure for FABM 5

FABM 5 is lime treated fly ash where the fly ash performs as both aggregate and part of the binder. It is primarily a sub-base, trench reinstatement or capping material.

1. Initial proportioning

1.1. For other FABM containing aggregate, the aggregate selection and proportioning are essentially fixed by the need to produce a mixture for immediate traffickability.

1.2. For FABM 5, which doesn't contain an aggregate in the normal sense, traffickability is not the same issue since overlaying before setting is the preferred approach. The mixture however has to be capable of supporting the compaction plant (pneumatic-tyred rollers only) before placement and compaction of the next lift which, ideally, should be carried out in such a way that direct trafficking of the FABM 5 layer does not occur. Thus the added lime proportion will be a function solely of the mechanical performance requirements.

1.3. Table 1 should be used for guidance in selecting the lime (or cement) proportion for testing at OMC and usually at a wetter water content to ascertain the sensitivity of the mixture to the accidental inclusion of excess water.

2. Assessment of the selected proportions using strength and or stiffness

2.1. For each of the chosen lime contents (or just the target mixture), after mixing together the conditioned fly ash and lime, and after allowing the mixture to stand for one hour before use, determine the optimum moisture content (OMC) using normal Proctor compaction in accordance with BS EN 13286–2.

2.2. Using the OMC and a wetter value, make sufficient strength specimens for each combination. Instead of 150mm diameter, these can be 100mm diameter cylinders with a height diameter ratio of 1 (or 2 for E determination) made either in HDPE moulds with a wall thickness of 10mm compacted to refusal using the vibrating hammer method in BS EN 13286-51 or refusal MCV specimens using the MCV apparatus.

2.3. Leaving the specimens in the HDPE moulds (or extruded in the case of MCV specimens), cure the specimens for the necessary periods at 40^{o}C (or at 20^{o}C for fly ash / cement binder combination) in sealed conditions and then test in accordance with BS EN 14227-41 for R_c, part 42 for R_t or part 43 for E to enable the selection of or confirmation of the required proportions against the specified or sought strength requirement.

3. Durability and volume stability

3.1. As for FABM 1 & 2.

Bibliography

- BS EN 14227-3. Hydraulically bound mixtures – Specifications – Part 3: Fly ash bound mixtures. BSI, London, UK.
- BS EN 14227-4. Hydraulically bound mixtures – Specifications – Part 4: Fly ash for hydraulically bound mixtures. BSI, London, UK.
- BS EN 13242. Aggregates for unbound and hydraulically bound materials for use in Civil engineering work and road construction. BSI, London, UK.
- BS EN 13286-2. Unbound and hydraulically bound mixtures – Part 2: Test methods for laboratory reference density and water content – Proctor compaction.
- BS EN 13286-4. Unbound and hydraulically bound mixtures – Part 4: Test methods for laboratory reference density and water content – vibrating hammer.
- BS EN 13286-41. Unbound and hydraulically bound mixtures – Part 41: Test method for determination of the compressive strength of hydraulically bound mixtures.
- BS EN 13286-42. Unbound and hydraulically bound mixtures – Part 42: Test method for the determination of the indirect tensile strength of hydraulically bound mixtures.
- BS EN 13286-43. Unbound and hydraulically bound mixtures – Part 43: Test method for the determination of the modulus of elasticity of hydraulically bound mixtures.
- BS EN 13286-47. Unbound and hydraulically bound mixtures – Part 47: Test method for the determination of California bearing ratio, immediate bearing index and linear swelling.
- BS EN 13286-51. Unbound and hydraulically bound mixtures – Part 51: Method for the manufacture of test specimens of hydraulically bound mixtures using vibrating hammer compaction.

In general usage the term 'fly ash' is used for pulverized coal ash but it can also cover ash from burning other materials. Such 'fly ash' may have significantly differing properties and might not offer the same advantages as ash from burning pulverized coal. UKQAA datasheets only refer to PFA / fly ash produced from the burning of predominantly coal in power stations.