Properties of engineered cementitious composite concrete (bendable concrete) produced using Portland limestone cement

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Abstract. Bendable concrete, also known as Engineered Cementitious Composite (ECC) is a type of ultra-ductile cementitious composites reinforced with fibres to control the width of cracks. It has the ability to enhance concrete flexibility by withstanding strains of 3% and higher. The properties of bendable concrete mixes (compressive strength, flexural strength, and drying shrinkage) are here assessed after the incorporation of supplementary cementitious materials, silica fume, polymer fibres, and the use of ordinary Portland cement (O.P.C) and Portland limestone cement (IL). Mixes with Portland limestone cement show lower drying shrinkage and lower compressive and flexural strength than mixes with ordinary Portland cement, due to the ratio of clinker existence being lower in the Portland limestone cement.

1.Introduction:

Conventional concrete is a prevalent construction material due to its multiple distinct properties, especially its durability and ease of handling. Ordinary Portland cement mixes are unbendable, with a strain capacity of only 0.1%, this lead for creating highly brittle and rigid concrete. The absence of bendability is the foremost cause of under strain failure, and it is the motivation for innovation leading to bendable concrete. Such concrete is reinforced with specially designed polymer fibres, being otherwise constituted from similar elementary constituents as conventional concrete, though with less coarse aggregate, being a type of ultra-ductile cementitious composite reinforced with fibre [1].

A relatively high proportion of bendable concrete powder could be added to cement to increase the content of the paste, and increased quantities of fine aggregate and superplasticizers or High-Range Water Reducing (HRWR) agents can be used in order to achieve better workability. For this type of concrete, coarse aggregates are not used, making the resulting material a mortar more than a concrete. ECC uses short, discontinuous fibres, typically at 2% by volume [1]. The incorporation of very fine silica sand with miniature Polyvinyl Alcohol fibres (nanometre thick) generates a slippery surface coating that permits...
the fibres to slip as they are loaded, preventing fracturing. This technique prevents the fibre from splitting and thus mitigates cracking. The establishment of bendable concrete thus basically depends on the interaction between concrete constituents, mainly between the matrix and the fibres; this fundamental factor governs concrete behavior, leading to modification techniques focusing on the interfacial zone to provide the preferred properties and use of suitable mineral admixtures to prevent ruptures and pull-out of fibre from the matrix.

Using bendable concrete containing 2% by volume fibre leads to an improvements in the capacity under tensile strain of 3 to 7% for ECC. Figure 1 shows bendable concrete performance under flexural loading, it should be noted that the concrete beam deforms without direct failure. The diverse constituents of bendable concrete work together to resist the load, making the resulting material up to 50 times more flexible than conventional concrete, as well as around 40 times lighter. Furthermore, its outstanding energy absorption makes bendable concrete appropriate for use in critical elements for seismic zones or microstructure tailoring.

![Figure 1. Behaviour of bendable concrete under flexural stress, [1].](image)

The use of cement with limestone may lead to reductions in CO₂ emissions, which makes it more environmentally sustainable [2]. Some research [3] has noted that clinker production releases CO₂ and that fuel used in the kiln and in the grinding mills also produces carbon dioxide and carbon monoxide. These gases are released into the atmosphere, contributing to global warming. This research aims to produce bendable concrete from local materials to create highly ductile mixes with adequate crack self-healing properties, as well as to produce bendable concrete from Portland limestone cement to improve sustainability.

2. Literature Review:

An experimental study [4] examined self-healing in bendable concrete under the influence of curing condition by recording pre-cracking time. For pre-cracked samples at the age of 14 and 28 days,
flexural strength increased, as a result of cementitious materials’ continuity of hydration. Nano-clay was considered to act as an internal water reservoir that aided the self-healing performance of bendable concrete without any supply of external water. Another study [5] was prepared to enhance the distribution of fibres by regulating the sequence of mixing, as unwanted plastic viscosity may be caused by poor fibre distribution, resulting in meagre hardened properties. The results revealed that the adjusted sequence of mixing did increase the tensile strain capacity of bendable concrete and improved fibre distribution compared with standard mixing sequences.

A further experimental study [6] examined synthetic and steel fibres, using the stress-deflection relationship of flexure to determine the flexural strength and toughness, the flexural strength equivalent, and the ratio of equivalent flexural strength. Another study [7] attempted to develop a bendable concrete with strong matrix for high tensile ductility, particularly at an early age; they thus evaluated the mechanical properties and drying shrinkage of bendable concrete with 70% mineral admixtures of combined fly ash FA and ground granulated blast furnace slag (SL) as a replacement of cement, with the results revealing that bendable concrete with mineral admixture combinations achieved a tensile capacity of 2.5% or greater at the age of 90 days. Bendable concrete made with slag and fly ash also showed successful increases in compressive strength, mainly at an early age, while adding slag into a matrix led to an increase in the drying shrinkage of bendable concrete. The lowest drying shrinkage at later ages was produced with 30% slag and 40% fly ash. Experiments in [8] were made on 36 diverse bendable concrete mixes, to assess the combined effect of the following factors on workability: water-binder (w/b), superplasticizer-binder (SP/b), and sand-binder (s/b) ratios. The results revealed that these factors affected mix workability. Beam deflection capacity is an indicator of material ductility, and mixtures were markedly diverse in deflection under changes of s/b. The mechanical properties of bendable concrete produced by using a high volume of mineral admixtures such as fly ash, slag, and silica fume were also investigated [9], and the results indicated that compressive strength has a converse relation with deflection, index of toughness, and fracture energy, but a direct proportional relationship with flexural strength, load at first cracking, and peak load.

3. Materials:

3.1 Cement

The cement used in the current research was Ordinary Portland cement (OPC) and Portland Limestone cement (IL). OPC is the general type of cement commonly used around the world, being the basic key ingredient for both concrete and mortar, while IL is comprised of finely ground Portland cement clinker mixed with a small amount of gypsum (calcium sulphate dihydrate).
The OPC used conformed to Iraqi specification No.5/1984 and the IL was produced by LAFARGE to conform to ASTM C595-Type IL. Table 1 shows the properties and specifications of the two types of cement.

**Table 1. Chemical and Physical Properties of Ordinary Portland Cement and Portland Limestone Cement**

| Chemical Properties | O.P.C % Weight | I.Q.S No.5/1984 Limits | Portland-limestone cement IL % Weight | ASTM C595-15 Limits |
|---------------------|----------------|------------------------|--------------------------------------|---------------------|
| Oxide content, %    |                |                        |                                      |                     |
| CaO                 | 60.8           |                        | 61.3                                 |                     |
| SiO₂                | 19.9           |                        | 17.7                                 |                     |
| Al₂O₃               | 4.7            |                        | 4.1                                  |                     |
| Fe₂O₃               | 3              |                        | 4.7                                  |                     |
| MgO                 | 1.5            | ≤5                     | 2.8                                  |                     |
| K₂O                 | 0.44           |                        | 0.5                                  |                     |
| Na₂O                | 0.11           |                        | 0.1                                  |                     |
| SO₃                 | 2.1            | ≤2.8                   | 2.3                                  |                     |
| Loss on Ignition (L.O.I) % | 2.7           | ≤4                     | 5.8                                  | ≤10                 |
| Insoluble Residue % | 1.2            | ≤1.5                   | 0.9                                  | -                   |
| Lime Saturation Factor % | 0.9           | ≤0.66-1.02             | 1.04                                 |                     |

| Physical Properties | OPC % Weight | I.Q.S No.5/1984 Limits | Portland-limestone cement IL % Weight | ASTM C595-15 Limits |
|---------------------|--------------|------------------------|--------------------------------------|---------------------|
| Soundness (Autoclave method) | 0.24%        | ≤0.8 %                 | 0.1                                  | ≤0.8%               |
| Specific gravity    | 3.15         |                        | 3.07                                 |                     |
| Setting Time        |              |                        |                                      |                     |
| Initial setting (min) | 130          | ≥45                    | 144                                  | ≥45                 |
| Final Setting (min)  | 230          | ≤600                   | 195                                  | ≤480                |
| Fineness (Blain m²/kg) | 309          | ≥230                   | 3681                                 |                     |
| Compressive Strength |              |                        |                                      |                     |
| 3 days (N/mm²)      | 20           | ≥15                    | 31                                   | ≥13                 |
| 7 days (N/mm²)      | 28           | ≥23                    | 38.3                                 | ≥20                 |
| 28 days (N/mm²)     | -            | -                      | 48.4                                 | ≥25                 |
3.2 Sand

Al-Akhaider sand was used, and the sieve analysis shows that it was in zone 2 according to the requirements of Iraqi specification No.45/1980 for particles passing standard sieves. It had a specific gravity equal to 2.61, an absorption percentage of 0.74, a Sulphate content (SO₃) of 0.3%, and the proportion of materials finer than a No. 200 Sieve was equal to 3.5%. No coarse aggregate is used to produce bendable concrete, though the sand showed reasonable results in combination with the cement and silica fume.

3.3 Silica Fume

Silica fume SF (condensed micro silica) with an activity index of 120% conforming to ASTM C1240-15 was used. The technical data for the silica fume is offered in Table 2.

| No. | property                                | SF     | ASTM C1240-15 |
|-----|-----------------------------------------|--------|---------------|
| 1   | Oxide content,% CaO                      | < 1    |               |
|     | SiO₂                                     | > 85   | min 85        |
|     | SO₃                                      | < 2    |               |
| 2   | Colour                                   | Grey   |               |
|     | Density                                  | 0.63   |               |
| 3   | Fineness (Blain m²/kg)                   | > 15000| min 15000     |
| 4   | Specific gravity                         | 2.3    |               |
| 5   | Accelerated pozzolanic Activity Index % at 7 days | 120 | min 105 |

3.4 Superplasticizer

A third-generation superplasticizer (Sika ViscoCrete -5930) was used, which conforms with the specifications of ASTM-C494 Types G and F. Superplasticizers are used to achieve an extreme reduction of water, improved flowability, and optimal cohesion. The reduction in w/c ratio means that the cement paste permeability reduces noticeably; hence, superplasticizer can be effectively used to improve numerous properties of concrete and avoid specific defects such as honeycombing.

3.5 PVA fibres

The fibres used to create the bendable concrete were polyvinyl alcohol (PVA), and one of the extraordinary features of these fibres is their strong bonding capability with cement paste. A layer of Ca(OH)₂, known as an interfacial transition zone, is formed around the PVA fibre, which appears as a white film; when using polypropylene, and glass, this does not occur. Both Ca⁺ and OH⁻ ions in cement slurry are attracted by PVA fibres and create a layer of Ca (OH)₂ around them; that is to say Ca(OH)₂...
layer plays an imperative role in increasing bonding strength between the fibres and the paste [15]. However, Polypropylene and glass fibres, despite their high tensile strength, are not coated with epoxy due to the absence of surface coating and thus have high susceptibility to alkali environments. The lengths of the PVA fibres used in the research were between 8 mm and 12 mm, with a diameter of 40μm, as seen in figure 2.

![Polyvinyl alcohol PVA fibre](image)

**Figure 2.** Polyvinyl alcohol PVA fibre

4. Experimental work

Two mixes were prepared:
- a cementitious composite mix with ordinary Portland cement.
- a cementitious composite mix with Portland limestone cement.

Superplasticizer and silica fume were added, and both mixes were reinforced with PVA fibres. Typical mixes that can be used for many structural applications with adequate ductility were prepared based on Dhawale et al [17] and Chethan et al [15], as well as many trial mixes executed in the laboratories of the University of Baghdad. The final mix design is detailed in table 3.

| Table 3. Mix design of ECC |
|---------------------------|
| **Cement** | SF | Sand | HRWR | water | Fibre |
| type | OPC | IL | - | Zone2 | 5930 | - | PVA |
| % | 1 | 1 | 0.9 | 1 | 0.012 | 0.44 | 0.018 |

4.1 Mould preparation

- 50x50x50 mm cubes were used for compressive strength testing.
- 50x100x400 mm prisms were prepared for the flexural strength test.
- 100x100x400 mm prisms were prepared for drying shrinkage test.
5. Results and Discussion

5.1 Compressive Strength

The compressive strength test was conducted according to ASTM C 109/C109M. The test results are shown in figures 4 and 5, after 28, 60 and 90 days curing for limestone Portland cement and Ordinary Portland cement, respectively.

Figure 3. Specimens used in the research

Figure 4. Compressive strength for Portland limestone cement
The results revealed that Portland limestone cement gained less compressive strength than Ordinary Portland cement due to the smaller clinker ratio in the Limestone Portland cement.

![Compressive strength of (O.P.C.) in bendable concrete](image)

**Figure 5.** Compressive strength for Ordinary Portland cement

### 5.2 Flexural strength

The flexural strength test was conducted according to ASTM C78/C78M. The flexural strength results are shown in figures 6 and 7 for Portland Limestone cement and Ordinary Portland cement, respectively, after 28, 60 and 90 days of curing.

![Flexural strength for Portland Limestone cement](image)

**Figure 6.** Flexural strength for Portland Limestone cement
The results showed that the flexural strengths of ordinary Portland cement mixes were higher than those of the mixes made with Portland Limestone cement due to the higher clinker ratio, which is responsible for the strength development.

![Figure 7. Flexural strength for Ordinary Portland cement](image1)

5.3 Drying Shrinkage

The drying shrinkage test was conducted according to STM C490/C490M. Figure 8 represents the drying shrinkage test after 1, 2, 3, 4, 5, 6, 7, 14, 28, 60, 90, 100, and 120 days of curing for Portland Limestone cement and Ordinary Portland cement.

![Figure 8. Drying Shrinkage of the Mixes](image2)
Figure 9. Compressive strength for ECC concrete

Figure 10. Flexural Strength for ECC

Compressive strength is directly proportional to flexural strength and inversely proportional to deflection. Incorporation of cementitious material such as fly ash, silica fume into a paste can efficiently increase the compressive strength at all ages, especially at early ages.

The results here show that specimens made with Portland limestone cement show lower drying shrinkage behaviour because the ratio of clinker in such cement help to maintain the specimens, causing less change than in specimens made with Ordinary Portland cement [14].

For the compressive and flexural strength tests, the results revealed that the specimens made with OPC gave better results than specimens made with IL cement due to the ratio of clinker, which encourages strength development with age.
6. Conclusions:
1- Weaknesses in the tensile properties of concrete have led to the invention of Engineered Cementitious Composite with unique and distinctive properties that include self-healing and good ductility.
2- Producing bendable concrete using Portland limestone cement is possible and offers reasonable compressive and flexural results and lower drying shrinkage behaviour than Ordinary Portland cement.
3- The drying shrinkage behaviour of concrete samples made with Portland limestone cement approaches that produced with Ordinary Portland cement.

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