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# Fibre reinforced roller compacted concrete transport pavements

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**Abstract**

Concrete pavements are generally more expensive to construct than asphalt pavements, and are thus mostly used in heavily trafficked sections and to reduce maintenance. The research work presented in this paper, however, indicated that the use of rapid construction techniques (such as roller compaction) and materials with lower embodied energy (such as low energy cements, recycled aggregates and recycled steel fibres) can lead to concrete pavements that are more economical and environmentally friendly than asphalt pavements (40% less energy consumption during the life cycle of the pavement). The first part of this paper presents an overview of this research, which was undertaken as part of the EU FP6 STREP project "EcoLanes" and investigated the development of long lasting rigid pavements made with steel fibre reinforced roller compacted concrete. The second part of the paper outlines the work undertaken for the development and optimisation of several trial concrete mixes. It is shown that the flexural behaviour of roller compacted concrete, under static loads, can be enhanced by the addition of fibres. Furthermore, the results of this study demonstrated the potential of recycling concrete pavements, at the end of their life, for the construction of new pavements.

**Notation:**

| | |
|---|---|
| CMOD | Crack-mouth-opening displacement |
| LLRP | Long lasting rigid pavement |
| NMSA | Nominal maximum size of coarse aggregate |
| RCC | Roller-compacted concrete |
| RTC | Recycled steel tyre cord |
| SFR-RCC | Steel fibre-reinforced roller-compacted concrete |

## 1. Introduction

Rehabilitation and extension of the surface transport infrastructure is essential for the economic and socio-economic development at regional, national, as well as international level. These activities normally require extensive investment and use of resources, e.g. the European construction Technology Platform has estimated that €600bn were required in the EU alone for the period 2005-10 (European construction Technology Platform, 2005). Therefore innovative construction materials and applications are essential to attain sustainable development of surface transport infrastructure.

The main element of surface transport infrastructure is the solid pavement, which can be constructed to be either flexible or rigid. Both of these construction methods have their merits and limitations, with their main structural difference being the way traffic loads are transferred to the subgrade (Yoder and Witczak, 1975). Flexible pavements are normally constructed with asphalt concrete, whereas Portland cement concrete is used for rigid pavements. Although asphalt pavements are currently the most preferred solution, the recent volatility in building material prices (as reported by the Portland Cement Association, 2009) is setting the basis for a change in pavement construction, with drivers being economic, as well as, environmental. The increasing demand to adopt more sustainable construction solutions is also driving the research on alternative types of pavement construction, such as concrete pavements, which in general have a longer working life than asphalt pavements (Embacher and Snyder, 2001).

In UK concrete pavements, steel reinforcement is primarily used to reduce the spacing of expansion and contraction joints as well as to minimise depth. However, steel fibres can be used to replace the conventional reinforcement and consequently speed-up the construction process, reduce costs, and increase safety on site (American Association of State Highway and Transportation Officials, 2001, American Concrete Institute, 1996).

Concrete pavements can be constructed using either a wet or a dry consistency mix. The wet mix is normally placed and compacted with conventional concreting techniques, which require the use of formwork, if slip-form construction is not employed. In addition, wet-mix concrete pavements require expensive expansion/ contraction joints. Dry concrete mixes can be placed with an asphalt paver and compacted by vibratory rollers (Fig. 1), forming roller-compacted concrete (RCC). RCC offers a high strength and durable concrete, at the speed of construction traditionally associated with asphalt (American Concrete Institute, 1995). Since the water content for RCC is determined by the optimum moisture content, for the same mix proportions, RCC has a lower water/cement ratio and, thus, higher strength can be achieved. This can lead to concrete mixes with lower binder content. It is noted that the level, surface smoothness and roughness of RCC pavements can be an issue for highway applications, and an asphalt overlay may therefore be required.

## 2. Background on SFRC pavements

### 2.1 Fibre Reinforcement

In general, the extensive use of steel fibres in concrete pavements is limited by the high cost of the fibres, especially in countries where labour costs are relatively low. The lowest price of industrially produced (termed here as “primary”) steel fibres is estimated at €700 per tonne, and it is at least 25% higher than the price of conventional steel reinforcement (MEPS International, 2009); and moreover, since the fibres are randomly distributed within the concrete matrix, larger volumes are required to achieve equivalent structural performance. This extra cost could be compensated through more rapid and labour efficient construction processes (e.g. RCC), especially in developed countries. For the rest of the world, an alternative to the expensive primary steel fibres is needed. As discussed by Pilakoutas *et al.* (2004), steel fibres recycled from waste streams, such as post-consumer tyres, have been shown to offer a cost effective alternative. These steel fibres are often considered a waste (or by-product) and since they cannot be disposed to landfill anymore, they are normally used as scrap feed in steel kilns where their value (Letsrecycled.com, 2009) ranges from €50 to €200 per tonne.

In recent years, it has been demonstrated in laboratory conditions (e.g. Pilakoutas *et al.*, 2004, Tlemat, 2004, Aiello *et al.,* 2009) that the structural performance of concrete reinforced with recycled steel tyre-cord (RTC) fibres is similar to that of concrete reinforced with primary steel fibres. RTC fibres therefore have the potential to offer an environmentally friendly way of dealing with tyre wire, and provide an economic alternative source of fibre reinforcement. It is noted that to best utilise this type of steel fibres, especially those produced from the mechanical processing of post-consumer tyres (such as shredding – elaborated by Shulman, 2004), it is essential to develop sorting treatments, which remove the rubber particles from the steel, minimise the geometrical irregularities of the RTC fibres, and arrive at the optimal lengths required to best utilise the steel strength (Pilakoutas *et al.*, 2004).

### 2.2 Cost-effectiveness

Although current material and energy prices already indicate that concrete pavements can be more cost-effective and energy efficient than asphalt pavements (Johnson, 2008); a further reduction could be achieved in the energy consumed during the production of concrete pavements. The main energy component of concrete pavements (from extraction of raw material to the placement of the pavement) is the energy used for the manufacture of cement and steel reinforcement (Zapata and Gambatese, 2004). Through the utilisation of low-energy cements and recycled materials, the energy consumption and consequently the cost associated with concrete pavements can be minimised. In addition the application of more efficient construction techniques, such as RCC (Fig. 1), can lead to further reductions in energy consumption and costs.

### 2.3 Applications and Research Needs

The first commercial applications of primary steel fibres in wet-consistency concrete pavements were undertaken in the early 1970s. These were followed by the construction of steel fibre-reinforced concrete (SFRC) airport taxiways as well as overlays of concrete pavements. Another application of SFRC pavements is ultra-thin white topping, where a relatively thin layer of SFRC (normally 50 to 100 mm) is paved over an existing asphalt pavement (Swamy and Lankard, 1974, Galloway and Gregory, 1977, Ibukiyama *et al*., 1984, Packard and Ray, 1984, American Association of State Highway and Transportation Officials, 2001). In addition, the use of steel fibres in cement bound road bases was trialled in order to improve the resistance to reflective cracking of asphalt overlays (Thom *et al*., 2000).

Despite the improved mechanical properties of steel fibre reinforced roller compacted concrete (SFR-RCC) pavements, there are very few known commercial applications. These applications involved the use of only certain types of primary steel fibres, whilst steel fibres recycled from post-consumer tyres have never been exploited. The limited application of SFR-RCC in pavement construction may be attributed to the practical problems associated with adding steel fibres in in-situ RCC and the complete lack of design recommendations. Limited published research work (e.g. Nanni, 1989, Houssien, 1992, Makoto *et al*., 2001) focused on investigating the effect of specific types of primary fibres and relied on small scale laboratory work on the mechanical properties of SFR-RCC. Fundamental research is therefore required on the effect that a number of parameters (such as the use of low energy cements, recycled aggregates and different types of steel fibres at several dosages) may have on the mechanical behaviour of SFR-RCC.

The use of secondary materials (such as RTC fibres and recycled aggregates) may trigger durability issues for SFR-RCC (as well as wet-consistency SFRC); and since very limited research work (e.g. Kosa and Naaman, 1990, Mangat and Gurusamy, 1987 and 1988, Granju and Balouch, 2005) and no standards can be found on the durability of SFRC, fundamental research is required to investigate these issues (especially for corrosion and freeze-thaw resistance).

In the past, a great deal of work has been undertaken towards the development of design guidelines for SFRC. The state-of-the-art in this field is represented by the guidelines published by RILEM TC 162-TDF (2002a, 2003) which utilise the findings of a Brite-Euram project (Brite-Euram 2002). However, these guidelines do not consider the use of SFR-RCC for pavement construction. Although the TR 34 design guide (published by the Concrete Society), is specifically for internal slabs on grade (Concrete Society, 2003), the same approach could be applied to the design of external paving (Concrete Society, 2007), with a few adjustments to account for the different nature of the loading and environmental conditions. For example, the high-cycle fatigue load, to which pavements are generally subjected, has to be considered in detail during the design process as it can affect significantly the mechanical properties and lead to structural failure. Although the current literature (e.g. Lee and Barr, 2004) indicates that the addition of steel fibres enhances the fatigue resistance of concrete, there is no consensus on the fatigue behaviour of SFRC and significant research effort is needed.

The above issues were addressed by the specific target research project “EcoLanes” (Economical and sustainable pavement infrastructure for surface transport), (EcoLanes, 2009). An overview of the research activities carried out by this project is presented in the following section along with the experimental work undertaken for the development and optimisation of SFR-RCC mixes.

## 3 Development of SFR-RCC pavements

The activities of “EcoLanes” aimed at developing sustainable pavement infrastructure for surface transport using RCC techniques and SFRC. The new construction concept aimed to reduce construction costs by 10-20%, construction time by 15%, energy consumption in pavement construction by 40%, minimise maintenance, use waste materials in pavement construction, and make tyre recycling more economically attractive. The three year project (EcoLanes, 2009), which started in late 2006, drew expertise from six European countries and its consortium comprised four universities, three industrial partners, the European Tyre Recycling Association and three end-users.

Through its nine work-packages, the project delivered new processes, models for life-cycle assessment and costing, and design recommendations. The results of the project were validated by constructing full-scale demonstration projects in four diverse European climates and economies (Cyprus, Romania, Turkey, and United Kingdom). To achieve the above aims and objectives, the project had to overcome scientific and technological barriers in fibre processing, concrete manufacture, and road design.

### 3.1 Fibre Processing

One of the main problems, encountered when mixing RTC fibres in fresh concrete, is the tendency of the fibres to form balls, which affects the mechanical properties of concrete (Pilakoutas *et al*., 2004). Fibre balling (Fig. 2b and 2c) is mainly caused by the irregular geometry of the RTC fibres (Fig. 2a), fibre length and relative proportion of fibres and aggregates. Laboratory work has shown that, if RTC fibres with aspect ratio greater than 200 are used or if the RTC fibres contain relatively large rubber particles, fibre balling can occur even at low fibre contents (less than 50 kg / $m^3$ of concrete). Thus, to reduce fibre balling in concrete, prototype fibre sorting / cleaning techniques and equipment were developed to minimise the geometrical irregularities and impurities of the RTC fibres. Initially, fibre processing was labour intensive and only small quantities of RTC fibres could be processed per day (i.e. few kilograms), while further development led to semi-automated processes, which could yield up to one tonne of RTC fibres per day. By the end of the three year project, 100 tonnes of RTC fibres were produced to the project specification. The specification requires the maximum rubber content not to exceed 1% by mass of fibres, and to minimise the amount of RTC fibres with length outside the range of 15-25 mm. RTC fibres are much thinner than most industrially-produced steel fibres, typically around 0.13 mm and, thus, the optimum fibre-concrete bond strength is attained when the RTC fibre length is between 15 to 25 mm (Tlemat, 2004).

### 3.2 Concrete Engineering

The introduction of steel fibres in RCC may lead to compaction problems that can affect the concrete density; damage may also be caused to the steel fibres during the compaction process. These issues were tackled successfully in laboratory studies of

SFR-RCC (elaborated in section 4), and were further assessed in full scale trials and during the construction of the four demonstration pavements.

To eliminate the technological barrier of adding steel fibres to RCC, various industrial processes and equipment were trialled to evaluate whether they could be used to successfully disperse steel fibres in dry mixes, and maximise the amount of fibre content added to the mix yet avoiding balling. During 2008-09, pre-demonstration trials were undertaken in four countries (United Kingdom, Romania, Turkey and Cyprus) to assess the suitability of conventional pan mixers for producing SFR-RCC. The results of the trials (held in conventional ready mix concrete plants) were satisfactory as the fibres were evenly distributed in the dry mix with minimal fibre balling (Fig. 3). During Spring/ Summer 2009, the same approach was adopted successfully for the construction of the four demonstration pavements (Fig. 4). The RTC fibre content of the SFR-RCC mixes ranged from 50 to 125 kg per $m^3$ (125 kg per $m^3$ for the UK demonstration). Following the successful construction of the four demonstration pavements, the end-user in Turkey has decided to adopt the technology of RCC reinforced with RTC fibres. The first commercial application (in late 2010) will comprise a 7.5 km rural road leading to a landfill site.

### 3.3 Road Design

The economic and sustainable design of concrete pavements is a complex calculation requiring input ranging from the material (physical, mechanical, chemical) characteristics and cost, energy inputs, cost of labour, equipment and fuel, to advanced numerical techniques. All these parameters were investigated through the development of the concept of the long lasting rigid pavements (LLRP) made with SFR-RCC (Boboc *et al*., 2010, Cososchi *et al*., 2009, Taranu *et al*., 2009), which also considered the environmental and cost life cycle of SFR-RCC pavements. The LLRP concept was technically validated (Fig. 5) on a circular accelerated testing facility, where sections of selected SFR-RCC mixes were subjected to 1.5 million load cycles (Cososchi *et al*., 2009). Experimental results indicated that there was no failure in any of the SFR-RCC sections, showing that (over a design life of 30 years) the proposed roads would survive at least 20.5 million-single-axis of traffic. Numerical analyses and parametric studies were also carried out to develop design algorithms and software for LLRPs (Taranu *et al*., 2009).

Results of the environmental and cost life cycled assessments, carried out for the demonstration pavements, indicated that the emissions for SFR-RCC pavements are 40% lower than those obtained for conventional asphalt pavements. In addition, the agency and user costs for SFR-RCC pavements are 10-15% lower than those determined for asphalt pavements (Hadjimitsis *et al.*, 2009).

## 4 Laboratory study of SFR-RCC mixes

RCC mixes are proportioned by adopting either the consistency tests approach or soil compaction approach (Choi and Groom, 2001). The authors adopted the latter approach, which involved determination of the optimum moisture content and assessment of mechanical behaviour and durability of trial mixes. The laboratory work carried out to evaluate the optimum moisture content, compressive and flexural behaviour of trial SFR-RCC mixes (Table 1) is summarised here, whilst a discussion on durability assessment can be found in Graeff *et al*. (2009, 2010). The absolute volume method (as elaborated by Gambhir, 2004) was utilised to determine the amount of materials required for each mix.

### 4.1 Materials

One type of low energy cement was used for the development of the trial SFR-RCC mixes. No admixtures were utilised in the concrete mixes.

Crushed rock (mainly porphyritic andesite/ granite type) was used as primary fine and coarse aggregate in mixes A to D. Crushed aggregates were used to reduce the risk of segregation and increase the quality of the bond between the paste and aggregate. The use of crushed aggregates also provides the stability required for the insitu rolling process. Mixes E and F contained recycled coarse aggregates, produced by crushing previously tested RCC specimens, whilst river sand was used for its fine aggregates.

The gradation curves for both primary and recycled aggregate, used for this work, are shown in Fig. 6. Although, for practical concrete mixes, it is recommended that the nominal maximum size of coarse aggregate (NMSA) be not larger than $^{2}/_{3}$ of the fibre length and should not exceed $^{1}/_{5}$ of the minimum size of the structural members (Japan Society of Civil Engineers, 1984a), a NMSA of 14 mm was used for all the mixes regardless of the fibre length. This was mainly done for comparison purposes, but also to further reduce the potential for segregation during production and placement, especially for the mixes incorporating the larger primary fibres.

Two types of steel fibres were used for the development of the trial mixes. The first one was primary steel fibres that were industrially produced according to BS EN 14889-1 “Type 1 – cold drawn wire” (BSI British Standards, 2006). This fibre type had a tensile strength of 1100 MPa and was a straight fibre with button ends (Fig. 7a), 54 mm long, and 1.0 mm in diameter. The second type was RTC fibres (Fig. 7b), which had an average diameter of 0.13 mm and a tensile strength of around 2000 MPa. Since the length of the RTC fibres was variable, a class specification was adopted to identify the length range of the RTC fibres used in each mix. Mixes C and D contained “EcoLanes Class C” RTC fibres (at least 80% of the fibres had length in the range of 1-15 mm, and no more than 10% of fibres were longer than 25 mm), while “EcoLanes Class B” RTC fibres were used in mix F (at least 40% of the fibres had length in the range of 15-25 mm, and no more than 20% of the steel tyre-cord fibres were longer than 25 mm).

## 4.2 Preparation of laboratory samples

Although the main method for compaction of RCC is the 10 tonne vibratory roller, it is impractical to use the roller for fabrication of laboratory samples. A number of alternative techniques and equipment can be used to prepare laboratory samples, e.g. vibrating table (including Vebe table), impact hammer, vibrating hammer, heavy pneumatic hammer, modified proctor procedure and Gyrator compactor (American Concrete Institute, 1995, Choi and Groom, 2001, Amer *et al*., 2004). In addition, other equipment that simulates the actual site conditions of RCC can be used to prepare RCC samples (Filho *et al*., 2008).

For the purposes of this research, the laboratory samples were prepared using a specialy designed apparatus which could simulate the actual site conditions of RCC compaction. The apparatus (Fig. 8) comprised a frame system to which a suitable vibrating hammer with a dead load was attached. Circular and rectangular end tamping plates can be used accordingly to consolidate cylinders, cubes and prisms. The use of such an apparatus was instrumental in achieving a high degree of consistency in the compaction process that is independent of the operator, and necessary to ensure repeatability of the tests.

## 4.3 Optimum Moisture content

The procedure used for the determination of the theoretical optimum moisture content of RCC and SFR-RCC was in accordance with the method adopted for the compaction of soils (BSI British Standards, 1990). For a given degree of compaction of a given SFR-RCC mix, there is an optimum moisture content at which the obtained dry density reaches a maximum value. Table 2 presents the values obtained for each trial mix. The addition of fibres to the mix increases the water demand (optimum moisture content) as part of it is retained by the fibres. In addition, the optimum moisture content evaluated for the mixes made with recycled aggregates is higher than the contents determined for the mixes with primary aggregates. This is likely due to the higher water absorption of the recycled aggregates and the old mortar attached to the aggregate (Hansen, 1992).

### 4.4 Compressive and flexural behaviour

All specimens, tested in compression and flexure, were cast in layers by using the apparatus outlined in section 4.2. A day after casting, the specimens were demoulded and placed in the mist room (+20° C and RH≥ 95) until the day of testing.

Compressive tests of RCC cylinders were undertaken to evaluate the peak compressive strength of the SFR-RCC trial mixes, in accordance to BS EN 12390-3 (BSI British Standards, 2002). The cylinders were 150 mm in diameter and 300 mm high. Table 3 shows the results obtained for the peak compressive strength of the trial mixes. The results indicate that the compressive strength of the SFR-RCC mixes is slightly lower than the strength obtained for the plain RCC mixes; this is mainly due to the air voids created by fibre addition. In addition, slightly lower compressive strengths were obtained for the mixes containing recycled coarse aggregates.

Bending tests of notched prismatic specimens (150 mm deep, 150 mm wide, and 550 mm long; 450 mm span) were carried out to evaluate the peak and post-peak flexural behaviour of the trial mixes. The tests were carried out according to the RILEM bending test (RILEM TC 162-TDF, 2002b). However, a four-point load arrangement was used instead of three-point load (Fig. 9), to minimise the overestimation of bending resistance, caused at the point of load application by the load-spreading effect (described by Timoshenko and Goodier, 1970). In addition, to avoid experimental errors and the effect of torsion on the deflection measurements (Copalaratnam and Gettu, 1995), a yoke was used as specified by Japanese standards (Japan Society of Civil

Engineers, 1984b). Mid-span vertical deflections were measured on both sides of the prisms using two transducers fixed to the yoke to account for any possible torsional effects. Another transducer was mounted across the notch mouth to monitor the crack mouth opening displacement (CMOD). The prismatic specimens were tested in a 100 kN servo-hydraulic machine in CMOD control by using the deformation rates specified by the RILEM bending test.

Figures 10 and 11 illustrate the bending test results for the six trial mixes. It is clearly shown that fibre addition improves significantly the post-peak flexural behaviour of RCC, with the primary steel fibres being more effective than the RTC fibres. However, a similar behaviour may be attained (up to a displacement of 2 mm), if a higher content of RTC fibres is added in the RCC mix (compare mix C with mixes D and F). The results also indicate that the flexural behaviour of RCC is not adversely affected by the addition of recycled aggregates; it is noted that longer RTC fibres were used in the mix with recycled aggregates, leading to the slightly better post-peak flexural behaviour.

## 5 Conclusions

Research performed as part of the European research project “EcoLanes” has developed SFRC pavements by utilising roller-compaction techniques and recycled materials, such as steel tyre-cord fibres, cement replacements, and recycled aggregates. The research findings of the project and the construction of four demonstration pavements have confirmed that the use of the above construction concept can lead to long lasting rigid pavements and reduce the construction cost and time (by at least 10%) as well as the energy consumption in road construction by 40%.

Results obtained from the mix development of the trial mixes have highlighted that fibre addition enhances significantly the post-peak flexural behaviour of RCC; this is despite the fact that fibre addition can reduce slightly the peak compressive strength of RCC.

The use of either primary or recycled steel fibres in RCC can lead to a similar flexural behaviour, if a higher content of recycled steel fibres is added to the concrete mix. Furthermore, the use of recycled concrete aggregates does not seem to affect the flexural behaviour of RCC. This indicates the potential of recycling RCC pavements, at the end-of-their-life, for the construction of new RCC pavements.

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**List of figures**

**List of tables**

Figure 1
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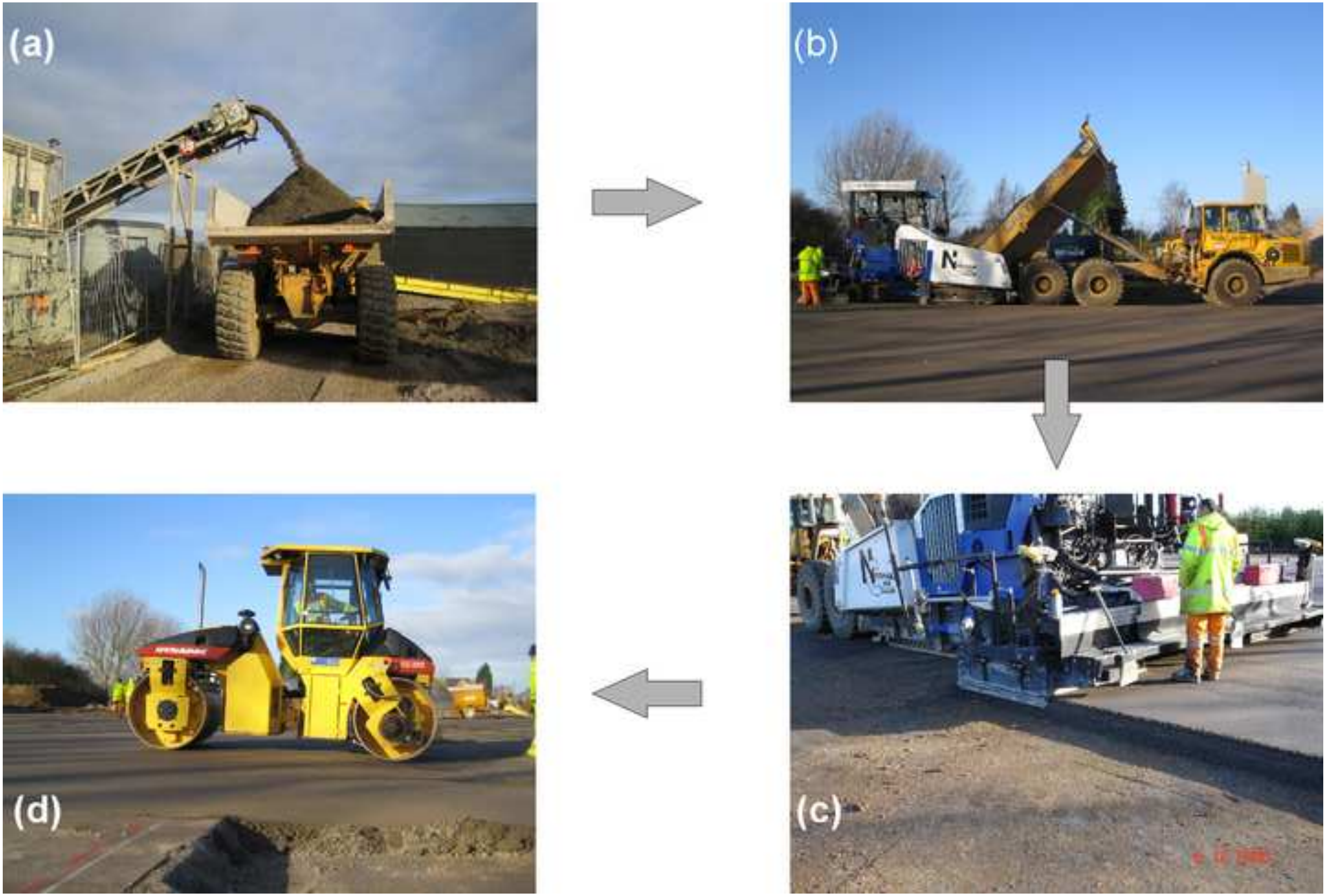

Figure2a

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Figure2b
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Figure2c
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Figure3a
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Figure3b
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Figure4a

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Figure4b
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Figure5a

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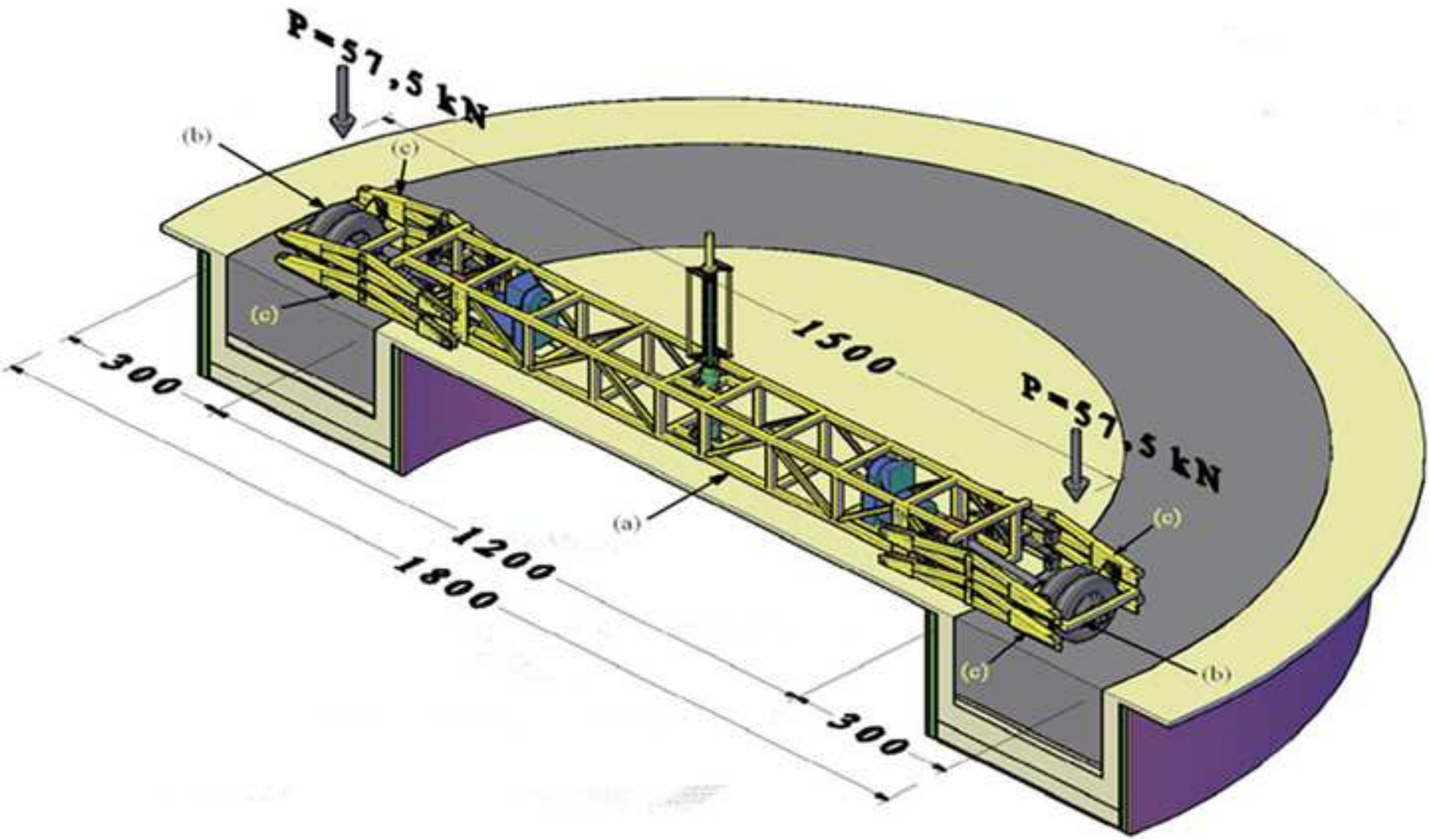

Figure5b
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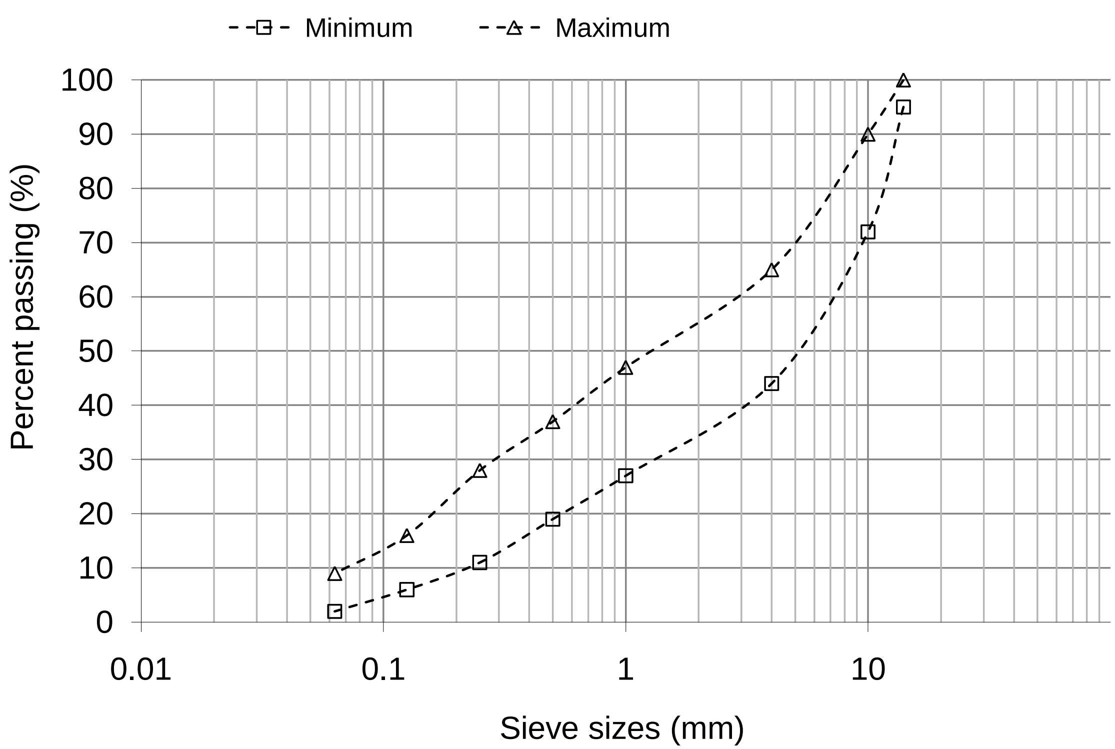
**Figure 6**



Minimum
Maximum
100
90
80
70
60
50
40
30
20
10
0
Percent passing (%)
0.01
0.1
1
10
Sieve sizes (mm)

Figure7a
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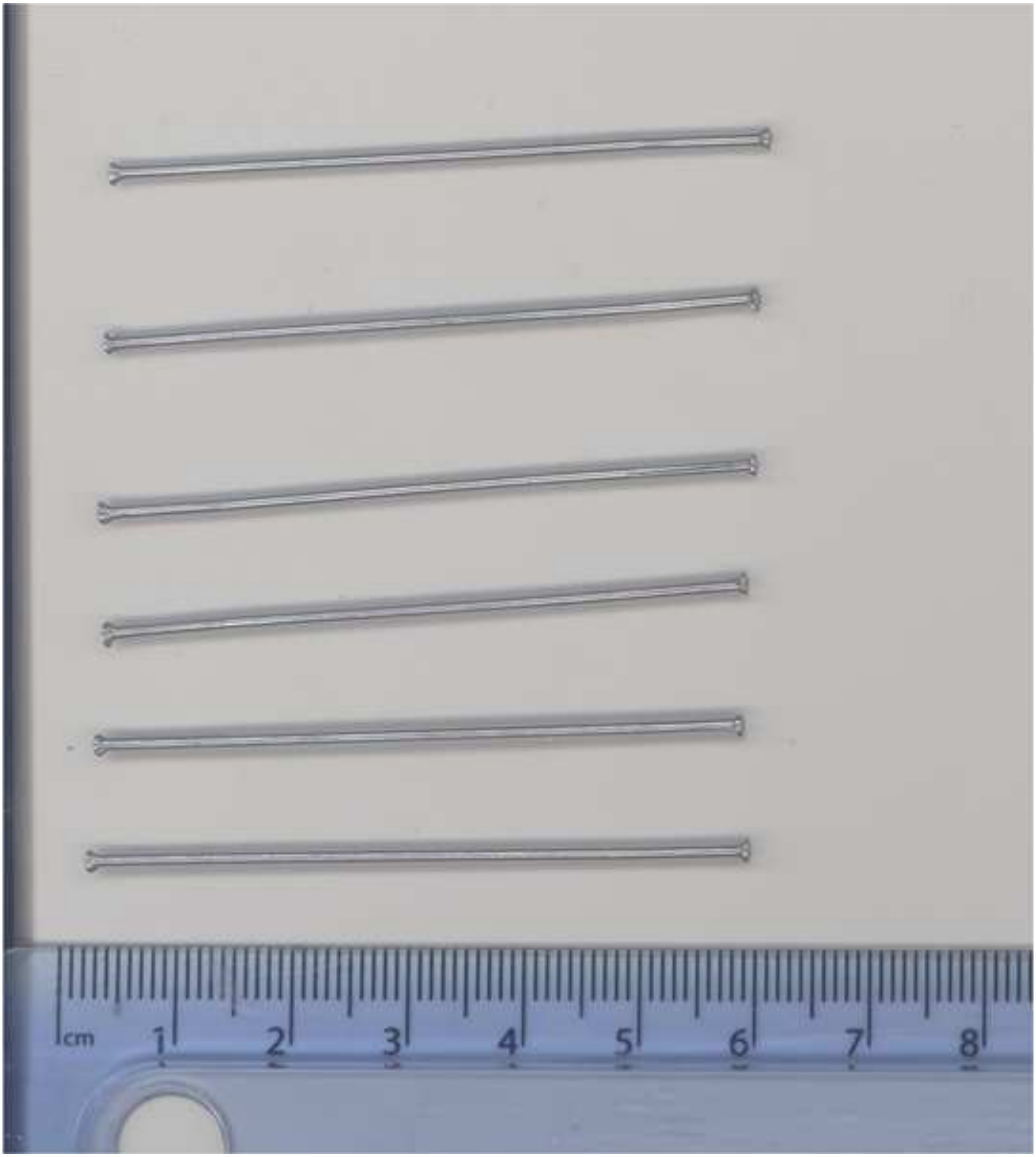

Figure7b
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Figure8a
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Figure8b
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Figure8c
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**Figure 9**

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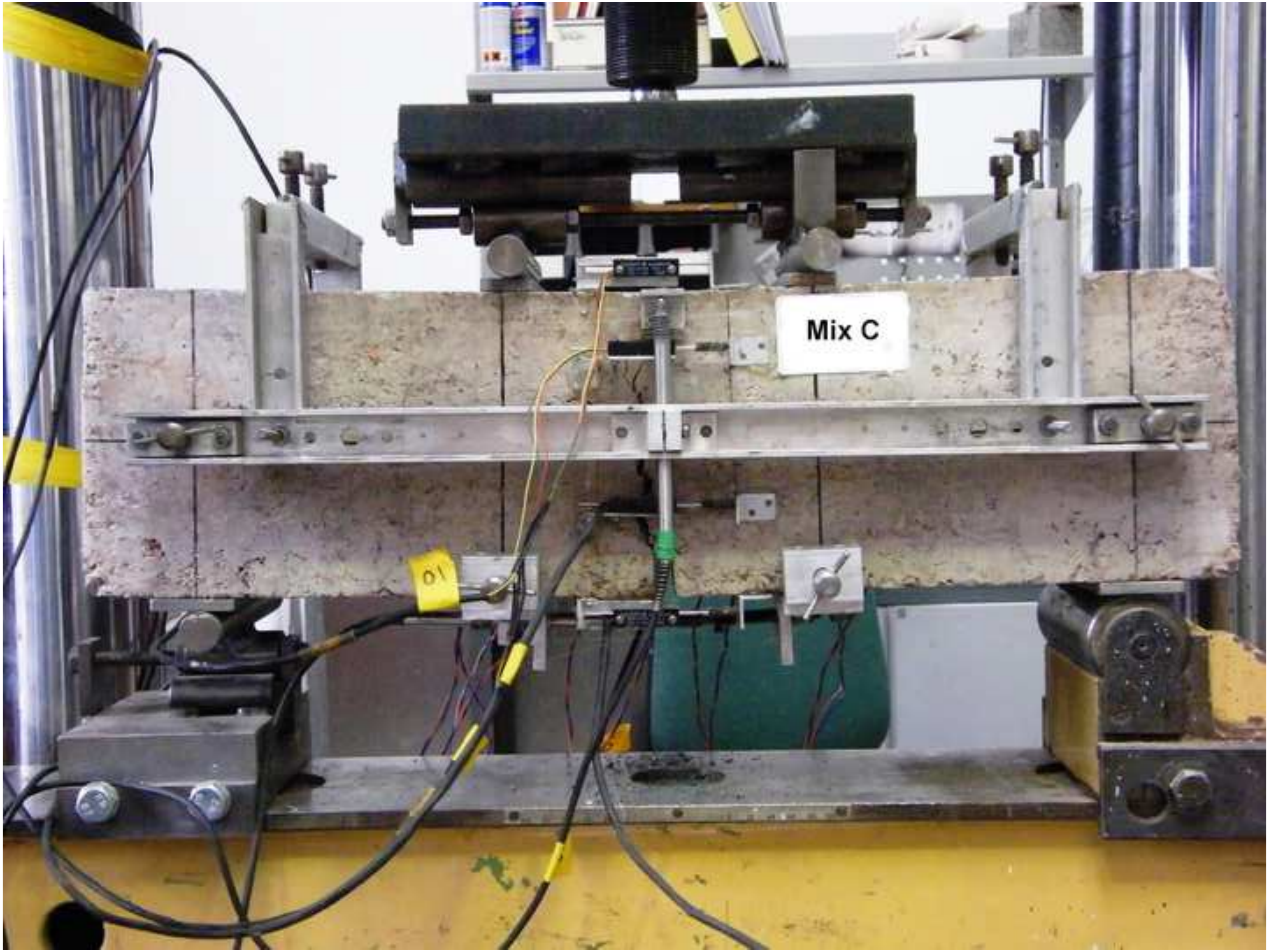
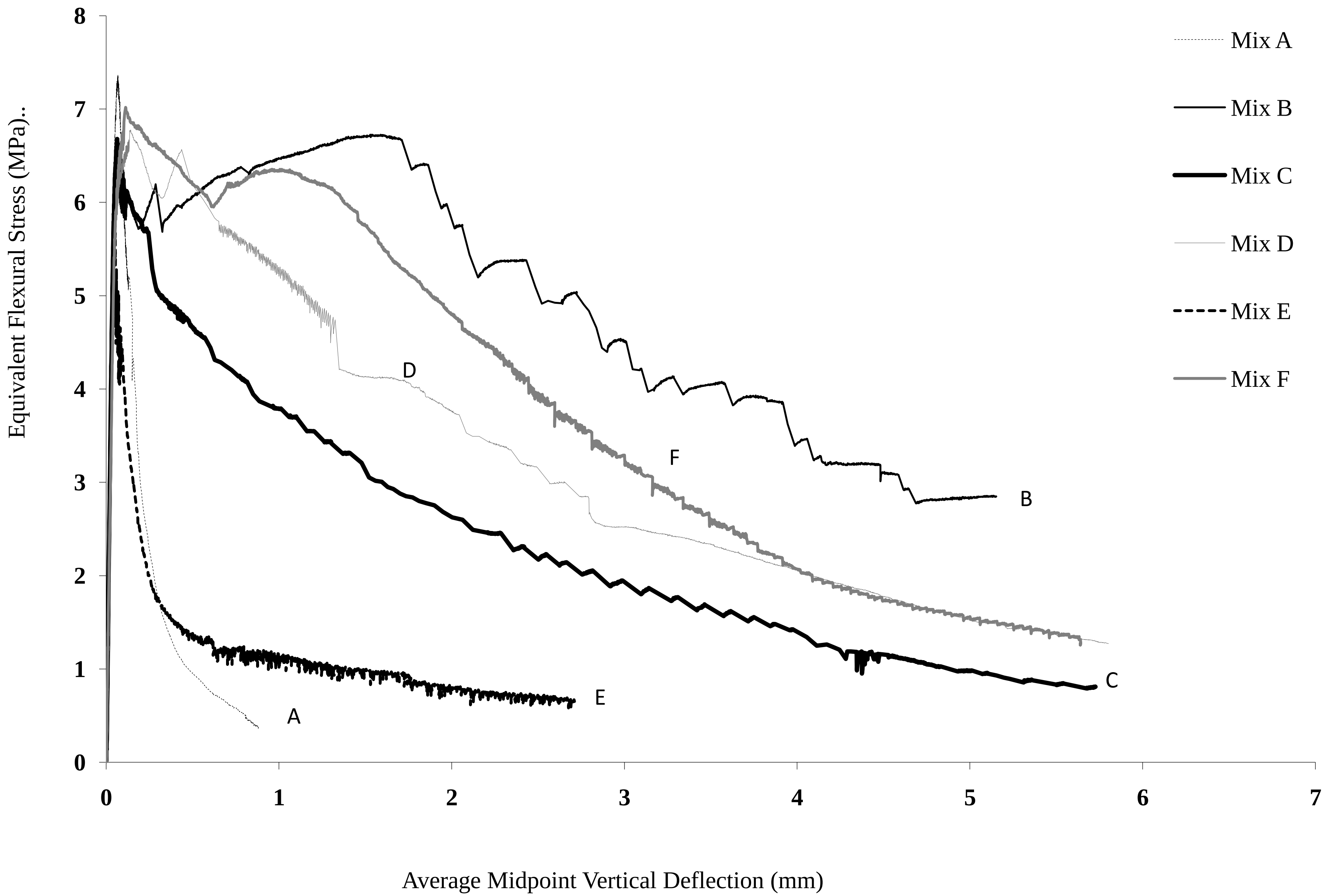
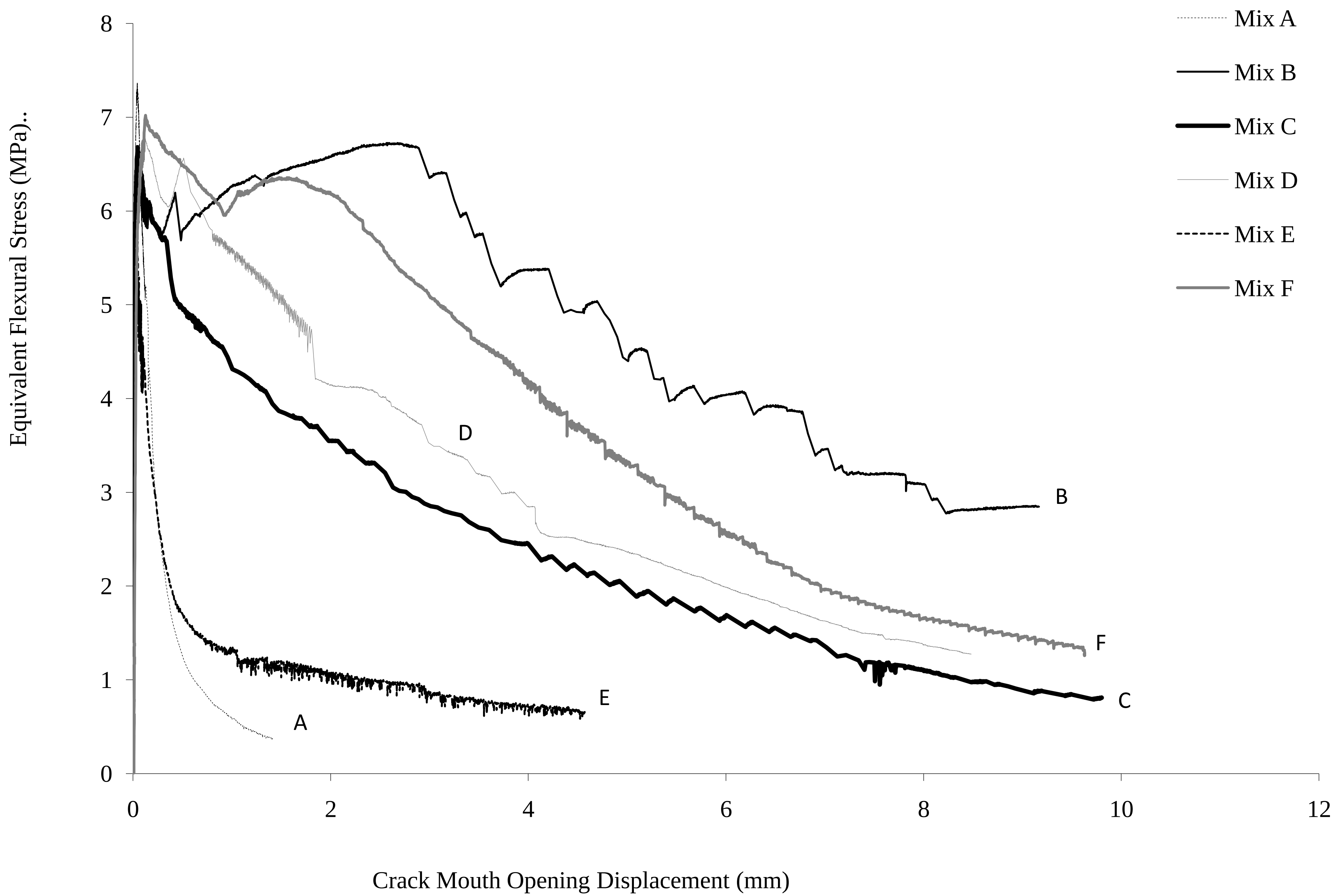


**Figure10**



Equivalent Flexural Stress (MPa)..
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
Average Midpoint Vertical Deflection (mm)
Mix A
Mix B
Mix C
Mix D
Mix E
Mix F
A
B
C
D
E
F

Figure11


Equivalent Flexural Stress (MPa)..
Crack Mouth Opening Displacement (mm)
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
Mix A
Mix B
Mix C
Mix D
Mix E
Mix F
A
B
C
D
E
F