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Induction heating technology for improving compaction of asphalt joints

ABSTRACT

Longitudinal and transversal joints in asphalt roads are permanently present in any pavement structure due to the construction procedures applied nowadays. These types of joints form discontinuities in the aggregate skeleton affecting the traffic loads distribution. Nevertheless, conventional joints construction procedures are basically focused on sealing the interface of the joint to avoid water infiltration. This study investigates the influence of the compaction temperature and the geometry of different joint designs. In particular, it proposes a new approach where iron particles are added to the asphalt mixture for allowing an induction heating process that locally increases the temperature either during the compaction of the joint or for an extra-compaction after construction of the joint. Results confirmed that high temperature during compaction of the joint leads to a better overall performance and that angular joints improve the interlock between the two interfaces. Likewise, it was shown that an extra-compaction process can significantly enhance the resistance of untreated joints against fracture and adhesion loss.

Key words: asphalt joints, induction heating, compaction process, temperature, iron particles, healing

1. Introduction

Durability and long-term performance of asphalt roads are significantly influenced not only by the quality of the pavements themselves but to a large extent also by the longitudinal and transversal joints from construction or from patching. Pavements are usually built during a certain timespan, meaning that they are produced and laid down during different time slots producing discontinuities between "old" and "new" materials. This implies that joints are almost inevitable. Further, the disruption of the aggregate skeleton in the asphalt mix, which is responsible for distributing the loads from the surface of the road to the layers below, limits the capacity to transfer traffic load from one pavement area to the other. Therefore, joints require special care since they stand for the weakest locations in the pavement structure.

These problems are a consequence of the current construction techniques, which have still much potential for improvement. Nowadays, construction of joints is manly focusing on avoiding water penetration into the pavement structure through the joint whereas only little attempt has been made to improve load transfer mechanisms. There are different methods for improving joints in asphalt pavements. It is usual to classify the joints according to the construction techniques used for improving the durability (Fleckenstein et al., 2002, Hean and Bernhard, 2014, Kandhal and Mallick, 1997):

- Applying rectangular thermoplastic joint tapes that are placed between the new and the old pavements for sealing and gluing together pavement parts. Typically, materials used for this purpose are polymer modified bituminous binders. The conventional technique implies the heating of the coating with a gas burner for the adhesion of the joint tape to the cold seam whereas the so-called self-adhesive joint tapes can be applied directly to the cold edge.
- Sealing the joint interface by applying bituminous coatings, such as grout paintings are mainly used for longitudinal joints.
- Pre-heating with torch or infrared heating device, avoiding burning of the bitumen. The quality of the joint is dependent on the heating temperature and time.

In spite of the fact that joints are important structural elements in pavements, relatively little research was carried out for increasing their performances. Most international publications about joints are technical notes with recommendations about how to lay out and compact a joint (AAPA 1997, Buncher 2012). Some reports contain a comprehensive literature review about the topic (Akpinar and Hossain 2004). Others (Kandhal and Mallick 1997, Kandhal 2007, Williams, 2011) compare long-term performance of selected longitudinal joints in view of different construction techniques. A general conclusion of these reports is that longitudinal joint cracking is primarily caused by substantial differences in density on either side of the longitudinal joint (density gradient across the joint). Most often, differences in the temperature cause insufficient bonding of the fresh and the old asphalt mixture creating significantly lower density in the longitudinal joint than in the rest of the pavement. This is also related to the regime of roller compaction and the geometry of the joining surfaces. When paving the first lane, one of its edges remains unconfined, leading to a lower density after compaction.

Most recently, *Wang and Oeser* (2015) analysed the possibility of transverse drainage of water through longitudinal joints in porous asphalt. They also considered different types of joints constructions, including pre-heating of the contact area with an infrared source in order to get hot joints which showed the best qualities. Furthermore, *Ghafoori Roozbahany et al.* (2013) investigated existing joint construction techniques, the influence of the temperature on the compaction of the asphalt joints as well as the effect of other inclined surfaces rather than vertical joints.

Taking into consideration the shortcomings of actual joint construction techniques and the optimum compaction regime and joint surface pre-heating, the use of the induction heating for sealing the discontinuities of the asphalt material during the construction of the joint could be an innovative application for this technology.

The existing induction technology offers a possibility to apply induction heating on asphalt pavement for healing purposes. It has been experimentally shown that microcracks generated by repeated traffic loads and thermal stresses at low temperature can be closed before they grow and propagate in the road structure (Garcia *et al.* 2013). This innovative process can be applied also for preventing ravelling on porous asphalt surfaces (Liu *et al.* 2010) and thus, for avoiding premature loss of cohesive bonds in the binder and/or adhesive bonds between binder and aggregates. The working principle of the induction heating process is based on applying an electromagnetic field generated with an inductor coil to the pavement. If the asphalt mixture is modified with electrically conductive or magnetically active particles or fibres, the application of alternating electromagnetic field will increase the temperature of the additives due to Joule effect. Then, the heat will reduce the viscosity of the bitumen which will flow closing cracks or repairing the bond with the mineral aggregates, as well as recovering the adhesive strength. However, it is also known that bitumen is sensitive to overheating such that heating method also means keeping the balance between crack healing benefit and heat induced degradation of the binder.

Different research groups have been working on the development of induction heating technology for healing asphalt pavements. During the last few years, they focused on studying the effect of different inductive materials on the heating performance of asphalt (Apostolidis *et al. 2016,* Jeoffroy *et al.* 2018). One of the main findings has been about the type and size of the particles in relation to the operating parameters of the induction coil such as the alternating frequency of the electromagnetic field (Jeoffroy *et al.* 2016). Further, it has been found that the temperature at which bitumen presents a Newtonian behaviour is crucial for the optimization of the healing process and that these thermal properties depend on the chemical composition of the bituminous material (Garcia *et al.* 2013, 2014, 2015). A recently published work has confirmed the feasibility of the concept at large scale by evaluating the healing levels of asphalt slabs after suffering controlled damaging procedures (Bueno *et al.* 2016). The work conducted provided the required experience for the application of the experimental concept for asphalt road surfaces maintenance purposes. Another application of this technology is shown in a new study where a numerical evaluation is used to simulate the compaction process of low temperature asphalt pavements assisted by induction heating (Apostolidis *et al.* 2017, Zhou *et al.* 2017).

In this context, induction heating by using an alternating electromagnetic field seems to be a promising technique that could improve the long term performance of joints obtained by standard construction procedures. Electromagnetic fields can penetrate the material and reach every spot of the joint, generating heat. Bitumen could flow deeper into the joints and improve bonding. Another important advantage appears in case of rehabilitation of an old joint, since repairing with this technique would mean less effort and better results than current standard procedures. In this way, healing capacity can be activated which will extend life and functionality of a road significantly.

In this study the construction of asphalt joints was reconsidered and a novel approach is proposed. Performance of the new joints was evaluated and compared to traditional construction techniques. The proposed solution is focused on the incorporation of electrical conductive additives into the asphalt material in order to improve the compaction process on both sides of the joint after locally reaching the required temperature by means of induction heating technology.

2. Experimental aspects

2.1. Materials and compaction process

In order to analyse the performance of conventional asphalt joints and experimental solutions, a number of different joint designs were built at lab scale. First, a lab compaction procedure was developed to obtain longitudinal joints in the centre of 1.8 m long asphalt concrete slabs. In order to reproduce the process applied in the field, a roller compactor was used for compressing the asphalt concrete mixture (AC 11) to a thickness of 4 cm (Canestrari *et al.* 2005). Different experimental parameters such as number of passes and temperature were controlled during the process. The compaction temperature was monitored using a full colour infrared camera with 640 × 480 pixels. In order to simulate the longitudinal joint, a defined amount of asphalt mixture was compacted as first lane of the system prior to the laying of the same amount for the second lane of the structure. Afterwards, a final compaction of the second lane plus the joint was conducted. Following this procedure, several asphalt slabs were compacted with different designs of joints (Table 1). They ranged from joints with different conventional commercial treatments (self-adhesive tape or bituminous sealing) to experimental designs including mixtures with iron particles as additives.

Design A, taken as control, included compacted slabs with a cold-hot joint where the first lane was compacted with one free edge at the later joint location. This means that this side of the joint was not subject to lateral confinement (Figure 1a and 1b). In order to assess the effect of the temperature difference during the compaction process, the first lane of the plate was allowed to cool down to 22°C before the asphalt mixture for the second lane was laid and compacted at high temperature (ca. 130 °C) (Figure 1c and 1d). Designs B and C reproduced the conventional solutions applied to asphalt joints nowadays (Figure 2). In these treatments, the edge of the joint was sawed after compaction of the first lane. In case of design B, a self-adhesive tape (TOK-Band SK® 1 cm thickness) was applied directly to the cold seam before compaction of the second lane. For design C, a commercial bituminous coating (TOK-Plast ®) was applied to the cold interface as sealing.

The experimental designs involved the use of iron particles with sizes between 0.6-1.0 mm as inductive additives. These were only incorporated into the asphalt mixture (14% wt. of mixture) close to the joint in order to use locally induction heating. Specifically, design D consisted in a hot-warm joint where the first lane was heated up to 90°C before the asphalt mixture of the second lane was laid and compacted at 130 °C (Figure 3). In this case, the use of the lateral confinement during the compaction of the first lane resulted in a vertical joint. For designs E and F, hot-cold joints were built with and without lateral confinement during the compaction of the first lane respectively. Afterwards, as additional steps, an induction heating treatment and an extra-compaction process with a portable cylinder (ca. 105 kg) after heating the joint area up to 130 °C were carried out (Figure 4). Finally, design G was prepared as a hot-warm joint similar to design D but, in this case, the first lane was compacted without lateral confinement in order to produce a free edge. It is important to remark that the method without lateral confinement (i.e. designs F and G) was expected to have some practical advantages because it would add better interlocking of the aggregate skeleton similar to angular joints and avoid the sawing process for the conventional treatments, thus saving also a significant amount of material.

2.3. Induction heating set up

The induction heating experiments were performed with a 30 kW induction heating generator at a maximum frequency of 80 kHz. The setup and dimensions of the induction coil can be found elsewhere (Bueno *et al.* 2016). The heating area around the joint was kept closely to 130°C during the extra-compaction process with the portable cylinder (Figure 4). To this aim, the compaction temperature was controlled using the infrared camera.

2.4. Mechanical characterization methods

2.4.1 Stiffness modulus and fracture resistance

Prismatic specimens (40 mm x 40 mm x 500 mm) were cut from the different slabs perpendicular to the joints in order to evaluate the stiffness and the fracture behaviour of the joints. Ten four point bending (4PB) tests from each design were carried out at 10°C after conditioning in a climate chamber overnight in order to characterize the so called stiffness modulus of bituminous mixtures in the linear viscoelastic range. Following the procedure described in the European standard (CEN 2012), the stiffness modulus was calculated by applied sinusoidal strains under 50 micro-strains at 10 Hz and measuring the deformation of the specimen as a function of time as well as the phase lag between the force and the displacement signal.

Further, also using the 4PB configuration, fracture tests under displacement mode (1 mm/min) at 0°C for the different designs of asphalt joints were performed.

Finally, specimens without joint were tested for evaluating the behaviour of the asphalt mixture (reference material, R1) as compared to the specimens with joints. Besides, specimens of asphalt mixtures with iron particles (R2) were assessed in order to evaluate the effect of these additives on the mechanical properties.

2.4.2 Adhesion performance at low temperature

Cylindrical specimens (100 mm diameter) of the joints were drilled from the experimental slabs. Then, direct tensile tests (DTT) were accomplished in displacement mode (10 mm/min) to measure the tension bonding capacity in the joint at low temperature (-20°C) (Partl and Hean 2002). Six specimens from each design were tested and the average maximum adhesion strength was taken as representative parameter of the adhesion performance. Moreover, the visual aspect of the interfaces was carefully examined in order to determine if the failure was caused by lack of adhesion or cohesion.

3. Results and discussion

The results obtained from the four point bending tests to evaluate the stiffness of the joints are shown in Figure 5a. It was found that the conventional treatments generally applied to the joints, designs B and C, presented lower values than the design A did. Likewise, all the experimental designs also showed better performance than the existing commercial solutions. In particular, design D, which simulated a hot-warm joint involving the use of the induction heating, obtained the highest stiffness value.

Regarding design E, two different treatments were carried out on an asphalt concrete slab, namely E0 and E1. One part of the slab was heated by induction in order to conduct an extra-compacting process (design E1) whereas in the other part no posterior treatment was used (design E0). The untreated specimens showed a similar behaviour as compared to those with design A. Both cases are hot-cold joints but in the case of design E0, the use of lateral confinement during the compaction of the first lane (vertical joint) provoked a lack of mechanical interlock between the two parts of the structure. As a result, this discontinuity of the granular skeleton through the system made the joint sometimes even not resistant to small vibrations from the cutting machine. In addition, the results from design E0 as compared to those associated to design D, clearly demonstrate the importance of the temperature during the compaction process. Design D with a hot-warm joint produced structures with much better mechanical properties than cold-hot joints compacted in designs E. Nevertheless, an extra-compaction after the induction heating procedure (design E1) improved the performance considerably.

In the same way, design G obtained better results than design A as a result of the high temperature of the first lane during compaction of the second one. Better performance was also found for the specimens of design F in comparison to design A. In this case, stiffness slightly increased due to the compaction temperature, but the extra-compaction process must still be optimized for getting values similar to design G. Finally, the evaluation of reference specimens with (R1) and without conductive additives (R2) revealed that an asphalt road with longitudinal joint can closely behave like a normal one without joint provided that the compaction temperature is well kept under control. Iron particles were found not to have a negative effect on the mechanical behaviour of the mixture.

Moreover, the resistance to fracture of the different designs can be analysed with the maximum force reached during the test under displacement control (Figure 5b). Again, it seems clear that the experimental designs D and G with hot-warm joints provided better load transfer. These specimens reached values up to four times higher than the conventional joints and comparable to the reference without joint (design R). These promising results are related to the temperature of the asphalt mixture in the first lane (ca 90°C) during the compaction of the second lane, demonstrating that thermal effects can improve the adhesion between both interfaces. It can also be observed that design E1 resisted similar forces against fracture at low temperature than joints with design D originally compacted at high temperature.

The positive influence of the extra-compaction at a controlled temperature around the joint can be observed clearly by comparing fracture results from specimens with design E0 and E1. Further, the fracture resistance found for design F was better than for conventional solutions. Nevertheless, low density obtained in the first lane during the compaction process (free edge) affects the performance of this kind of design such that the extra-compaction process does not improve the fracture resistance of the initially compacted hot-warm joints.

Figure 6 compiles a set of images with details of the fracture type obtained for each kind of joint. It shows that the crack in design A is following the weakest path in the mixture even going through mineral aggregates sometimes (Fig. 6a). Designs B and C presented sharp fractures placed on the interfaces due to the loss of adhesion in the joints. It can be observed that the crack is defined by the bond between the adhesive tape and the edge of the sawed face of the first asphalt lane. Also, vertical fractures were observed in the specimens with joints of design D as a result of lateral confinement during the compaction of the first lane. In this case, the joint was compacted as hot-warm and the face of the fractures showed some roughness indicating the existence of interlocking. However, it seems clear that the crack followed the vertical path coinciding with a still weak joint.

The influence of the compaction process after induction heating is showed in Figure 7. As shown in the previous analysis, cracks usually follow the joint path during a fracture test. In this case, specimens from areas subject to the experimental procedure (design E1) did not fracture through the joint. This fact confirms that the treated joint was not the weakest point in the specimen and that the material behaves as a uniform asphalt mixture without joints. This type of fracture could be observed for joints with designs F and G as well.

Finally, the adhesion test results of the different joints are shown in Figure 8. In this case, joints with design A presented the worst performance within the conventional solutions whereas the commercial treatments with self-adhesive tape (design B) and sealing coating (design C) showed results slightly lower than the experimental design D. Nevertheless, results obtained from both types of designs E showed that the adhesion performance of these cores was worse. This could be related to the lateral confinement during compaction of the first lane and the resulting vertical joint as well as to the temperature during compaction. For designs F and G, better interlocking of the aggregate skeleton was obtained. This positive effect with inclined interfaces was already suggested by others (Ghafoori Roozbahanay *et al.* 2013). However, the difference between the conventional and experimental solutions was not as significant as compared to the evaluation of the fracture resistance.

Further, some details of the fracture interfaces of different types of joints are shown in Figure 9. In the case of design B, the fracture at low temperature was found to propagate through the adhesive tape and not in the interface with the sawed edge of the compacted asphalt lane. Moreover, it could be observed that the fracture in joints with design D was quite straight and rough, whereas fractures for design F were asymmetric and not located in the middle of the specimens.

4. Conclusions

This work showed the experimental results of a research project that aims to improve the compaction of the joint area as well as interlock of the aggregate skeleton of the asphalt mixture, responsible of distributing traffic loads from the pavement surface to the lower layers. A solution was proposed with locally incorporating electrical conductive additives into the asphalt material to allow a compaction process at a proper temperature in both sides of the joint. In order to obtain the required temperature, an induction heating process was carried out either before compacting the second lane or after the conventional construction of the joint. In one approach, the first lane already compacted was partially heated up just before laying the asphalt material for the second lane. In the other approach, the joint area was heated up in order to allow an efficient extra-compaction. Moreover, these solutions add healing capacity which will allow the extension of the road life.

A number of slabs with different conventional and experimental joints designs were compacted by roller compactor in order to evaluate their mechanical and adhesion performances. Results confirmed that high temperature on both sides of the joint during compaction improved the performance as compared to commercial treatments. For hot-cold joints, induction heating allowed a posterior local heating process followed by an extra-compaction focused on the joint area. This technique increased the density in the joint and, therefore, the interlocking throughout this discontinuity. In contrast, it seems that generally the extra-compaction process does not improve the response of hot-warm joints. The effect of the lateral confinement during the compaction of the mixture in the first lane was evaluated as well. The process without the lateral confinement led to a kind of angular joint which adds better interlocking of the aggregate skeleton.

In general, it can be concluded that the use of induction heating to improve the performance of longitudinal joints can lead to more durable asphalt concrete pavements. In the same way, the extra-compaction process seems to positively affect only on the originally compacted hot-cold joints. Moreover, these solutions with electrical conductive additives can be considered as advantage in terms of maintenance, since the inductive heating potential allows re-treating the joint such that the interlock, even after service, can be reactivated again. Nevertheless, future work must focus on the study of further different configurations of joints and the evaluation of factors such as the induction heating time and the compaction temperature, which depends on the type of mixture (bitumen) as well as on the type and amount of inductive additive. These operating parameters will be analysed in a parametric study in order to optimize the application.

Conflict of interest

The authors declare that no conflict of interest exits.

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Table 1. Conventional and experimental joint designs (designs A, B and C without cast iron particles).

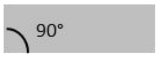
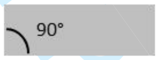
Design	Type of Joint	
Design A		Free edge / Hot-cold joint
Design B		Sawed and self-adhesive tape
Design C		Sawed and bituminous coating
Design D		Lateral confinement / Hot-warm joint
Design E0		Lateral confinement / Hot-cold joint
Design E1		Lateral confinement / Hot-cold joint / Extra compaction
Design F		Free edge / Hot-warm joint / Extra compaction
Design G		Free edge / Hot-warm joint

Figure Captions

Figure 1. Detail of compaction process for design A joints. First lane after compaction without lateral confinement (a, b). Real image (c) and IR-image (d) with the temperature distribution for a hot-cold joint during the compaction of the second lane.

Figure 2. Self-adhesive tape applied to the interface in joints design B (left) and bituminous sealing applied to the interface for joints design C (right).

Figure 3. IR-image at the beginning of the compaction of a slab with joint design D.

Figure 4. Details of the induction heating treatment and extra-compaction of the joint design E.

Figure 5. Mechanical properties of the different joint designs. (a) Stiffness at 10°C (up) and (b) maximum forced reached until fracture at 0°C (down).

Figure 6. Details of fractures for different joint designs.

Figure 7. Details of fracture path in specimens with joint designs E0 and E1.

Figure 8. Adhesive properties of the different joint designs.

Figure 9. Details of fractures after direct tension test.

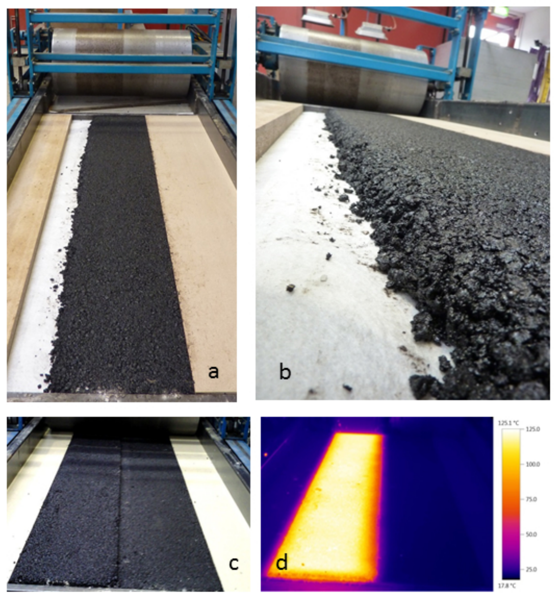


Figure 1. Detail of compaction process for design A joints. First lane after compaction without lateral confinement (a, b). Real image (c) and IR-image (d) with the temperature distribution for a hot-cold joint during the compaction of the second lane.

254x190mm (96 x 96 DPI)

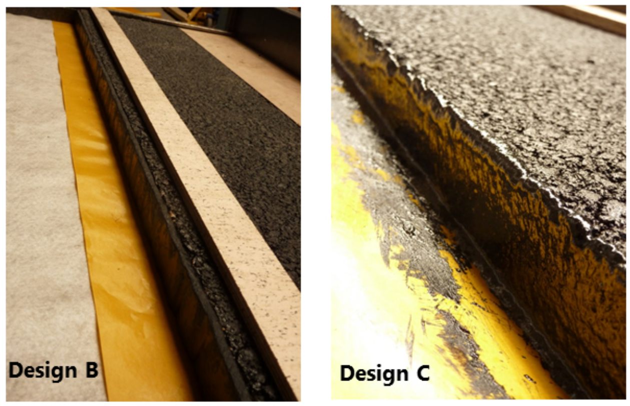


Figure 2. Self-adhesive tape applied to the interface in joints design B (left) and bituminous sealing applied to the interface for joints design C (right).

254x190mm (96 x 96 DPI)

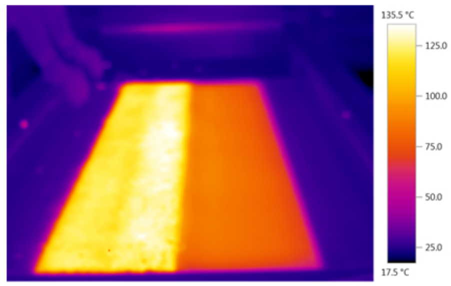


Figure 3. IR-image at the beginning of the compaction of a slab with joint design D.

254x190mm (96 x 96 DPI)

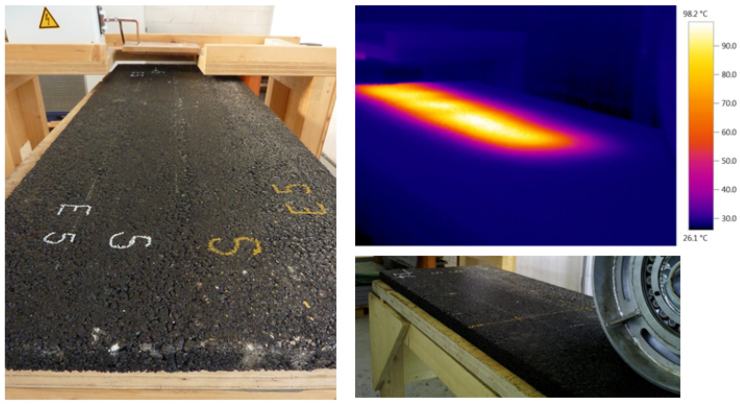


Figure 4. Details of the induction heating treatment and extra-compaction of the joint design E.

254x190mm (96 x 96 DPI)

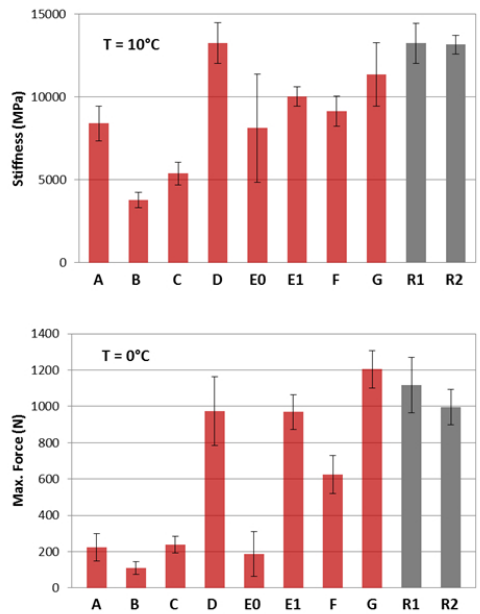


Figure 5. Mechanical properties of the different joint designs. (a) Stiffness at 10°C (up) and (b) maximum forced reached until fracture at 0°C (down).

254x190mm (96 x 96 DPI)

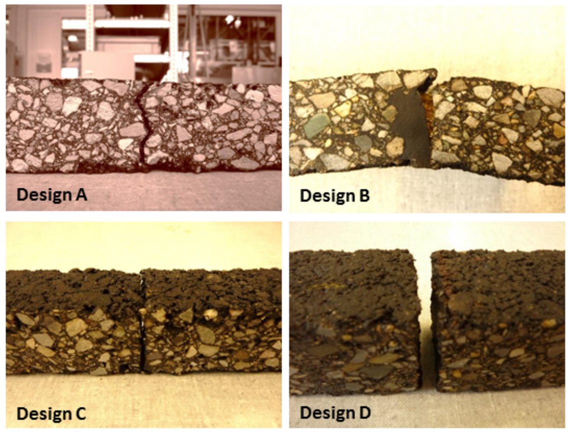


Figure 6. Details of fractures for different joint designs.

254x190mm (96 x 96 DPI)

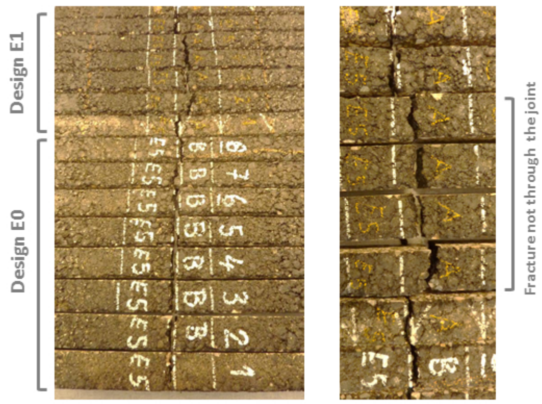


Figure 7. Details of fracture path in specimens with joint designs E0 and E1.

254x190mm (96 x 96 DPI)

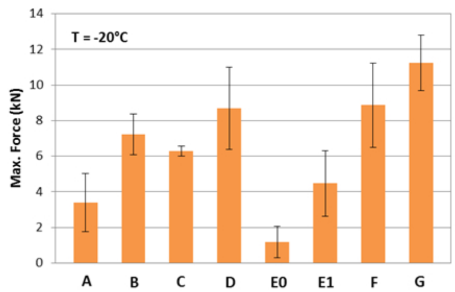


Figure 8. Adhesive properties of the different joint designs.

254x190mm (96 x 96 DPI)

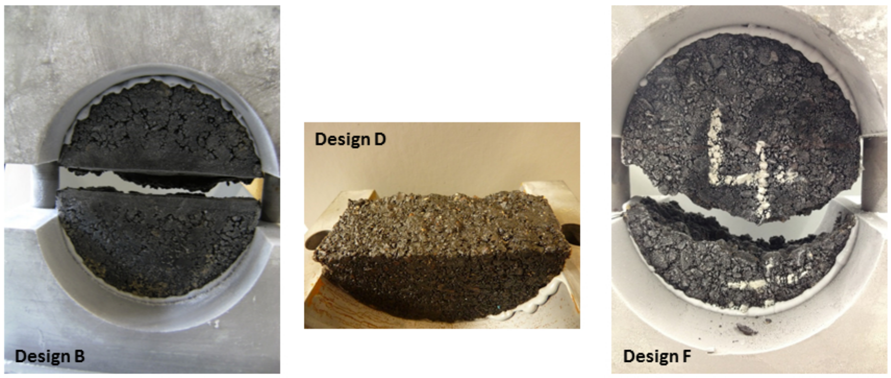


Figure 9. Details of fractures after direct tension test.

254x190mm (96 x 96 DPI)